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STAR

ITT AEROSPACE / OPTICAL DIVISION

FINAL REPORT

MULTI-SPECTRAL IMAGE DISSECTOR CAMERA SYSTEM

Contract NAS5-11617
National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

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1.0 INTRODUCTION

The Multi-Spectral Image Dissector Program was awarded to ITT in October of 1968 for the purpose of evaluating the image dissector sensor for the Earth Resources program. Attractive features of such a system were predicted from the performance of Image Dissector Cameras on Nimbus 3 and 4 and on the ATS-3 Satellite. In the multi-spectral configuration, a single image dissector tube, operating at its optimum resolution, includes three sampling apertures and associated spectral filters to permit continuous line scan of three spectral bands simultaneously. The use of such a system provides high quality imagery from a system having the inherent registration capacity made possible by a single optics, tube, deflection assembly, and housing. The output from the system consists of three simultaneous channels of image video, continuously recording the ground data on relatively low bandwidth tape recorders for data storage and transmission.

In the performance of the contract two models of the camera system were constructed; a laboratory breadboard, followed by an Engineering Evaluation Model. A total of eight tubes were constructed for the system. It is interesting to note that the first tube constructed against the end specifications was successful in performance such that it was used in all following laboratory and field evaluations. Only two complete tubes were constructed prior to that to gain experience in multichannel techniques. Four single aperture tubes were purely experimental to evaluate a unique method of applying the spectral filters, and one tube for a backup to the operational tube. The backup tube was also a single tube order, resulting in a satisfactory operational sensor tube. The tube technology is shown to be practical and economical.

A major activity of the study was the evaluation of the potential results of the system. Since the sensitivity and signal characteristics of the sensor follow calculated values very closely, it was possible to apply a number of variables to the system and optimize a system configuration. Using contrast and reflectance data supplied by NASA, comparable to those being used at the time by the studies on the Return Beam Vidicon System, we were able to define the ground resolution obtainable for low contrast definition features at the targeted signal to noise ratio of 1.8. As shown later in the proper section, the system was considered able to meet the criteria and be highly competitive with the RBV system.

Promising results from the early study and breadboard activity led to the construction of a fully operating system, including a camera of the general electrical design of an end system, optics that had sufficient spectral and spatial frequency response, and a test bed that would be capable of demonstrating the sensor performance. Figure 1-1 shows the Engineering Model Camera on the test bed, where a transparent scene or test pattern may be moved past the light source and be detected by the three simultaneous line scans in selected colors. In addition to the sensor test bed, an image reproducer was constructed, having the capacity to reconstruct full color images from the camera system. The sensor electronics contains timing and control signals which properly synchronize the color scanning and reproducing process. The color image reproducer is shown in Figure 1-2.

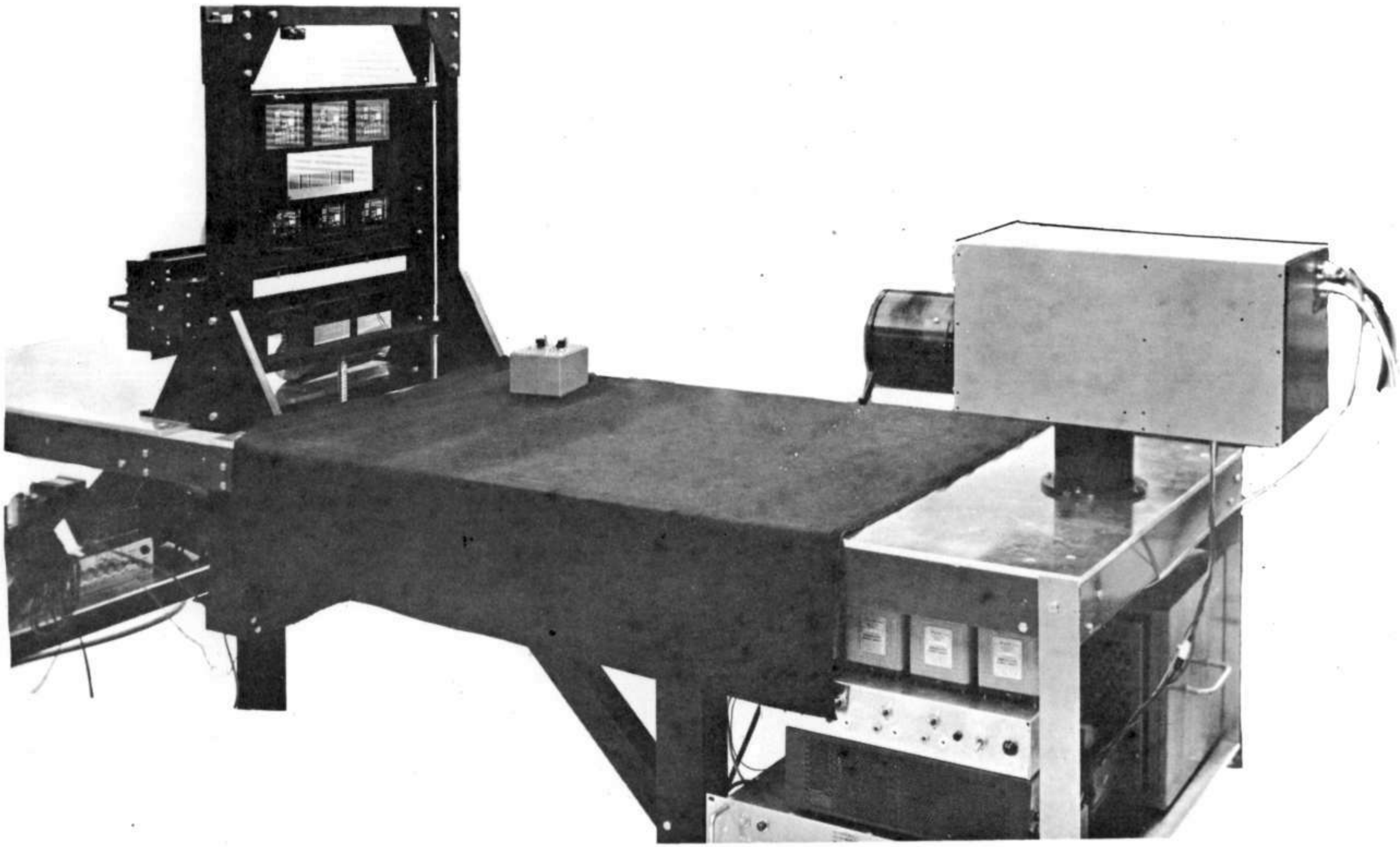

Figure 1-1. Engineering Model Camera on Test Bed

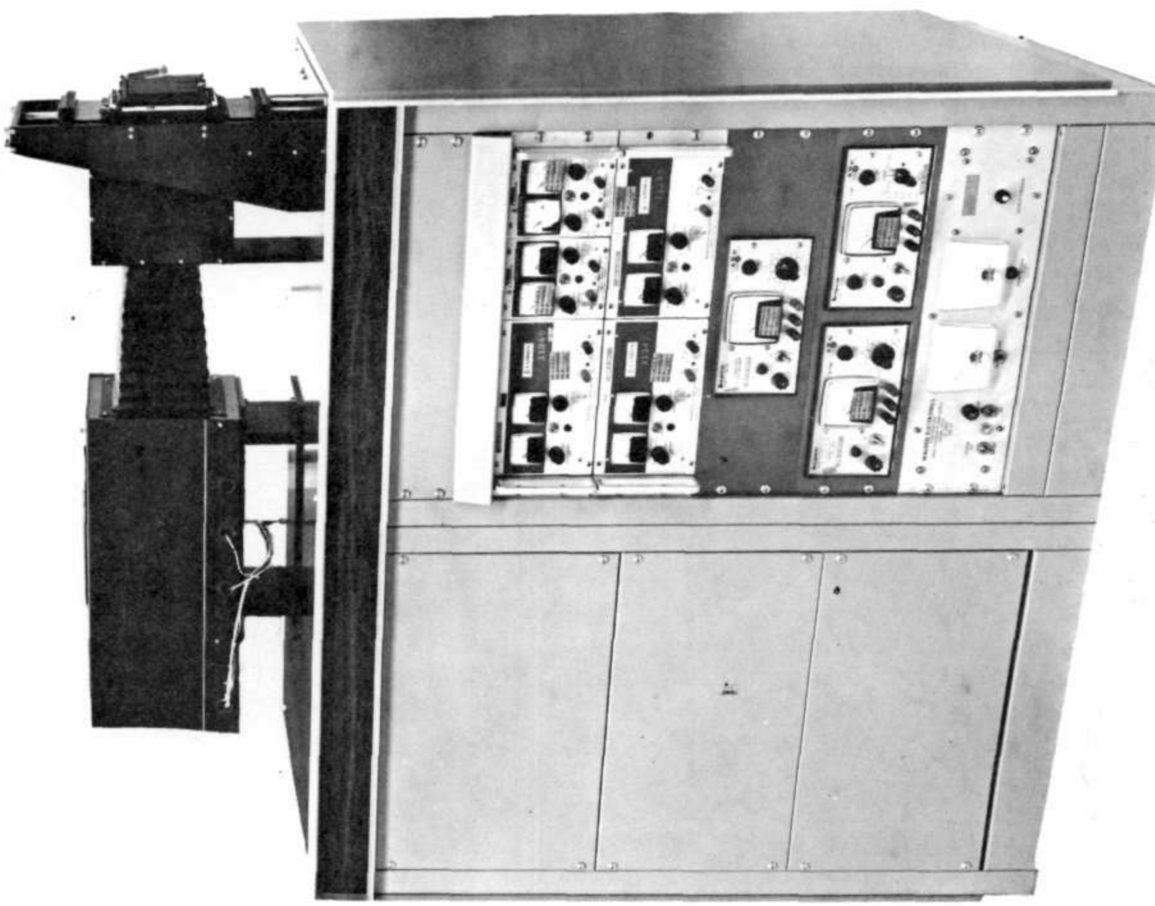

Figure 1-2. Color Image Reproducer

Again, the results from laboratory tests and evaluation of the resulting imagery were encouraging. The images reproduced indicated a capability for 200 foot elemental resolution from a 100 nautical mile swath, with a high degree of registration (within one element at the edges of the scene) under conditions of direct reproduction. No unusual techniques were required to register the three color inputs. The first high quality color image was generated in December of 1970. Copies of the scene were distributed to interested persons at NASA at that time. A copy of that scene is given here in Figure 1-3.

From the successful laboratory results, NASA requested that further tests using outdoor scenes be considered. Rudimentary tests were performed at the ITT facility using a simple nodding mirror. Limitations in platform stability prevented high quality image generation, but the scheme did permit evaluation of the system under full sunlight conditions and the opportunity to make use of spectral filters roughly matching those of the end requirement. The extended red response of the sensor became evident, and again permitted optimism in the operational capability of this system. Figure 1-4 is a scene at the ITT facility, using these system components.

By this time it was evident that the system had promise as a potential spacecraft instrument. An opportunity for space flight program did not exist. However NASA became aware of the availability of aircraft from the USAF at Rome Air Development Center, Rome, New York, and permitted ITT to work with RADC in the flight and evaluation of the system. An initial program of flight on a low altitude aircraft was terminated when it was learned that

Figure 1-3. Color Image - Salton Sea

Figure 1-4. Color Scene - ITT

Photo No. 72-9-0096

a high altitude jet aircraft would become available. The camera unit was therefore modified to withstand a more rugged environment and high altitudes. Two test flights in March of 1972 demonstrated system compatibility but indicated several areas of needed attention. The camera was reworked to improve its high altitude capability, and had several other alterations. The most significant of these was the adaptation of a NASA supplied roll gyro to provide direct compensation of the roll of the aircraft into the magnetic deflection system of the camera. In this way, the raw video from each color channel was already corrected for motion of the aircraft and would need no added pre-processing upon reproduction. The cooperation of the USAF personnel was exceptional and permitted the completion of test flights in June, 1972. The results of these flights are only partly evaluated, and a small number of the potential images reproduced. These are described and shown in detail in a later section of the report. The evaluation of the data and generation of imagery from the completed flights has been curtailed by the completion of the program at this time.

From the engineering and scientific studies and experience performed to date on the Multi-Spectral Image Dissector Camera program we have demonstrated that the goals of the system have been met as required, and that the technique has been proven theoretically capable of achieving the detection of small, low contrast ground targets from the satellite conditions specified. In addition, both the sensor tube and system have demonstrated a history of quality, reliability, and ruggedness that qualify it for future exploitation as a spaceborne or airborne system.

2.0 EQUIPMENT DESCRIPTION

2.1 General Description

The equipment to be described in this final report will be that of the Engineering Evaluation Model Camera as presently configured for the aircraft flight tests. For this application certain timing functions have been changed from that originally designed for the evaluation model in order to better interface to the flight profile and instrumentation tape recorder used for in-flight data storage. Included in the airborne system are the camera unit, camera control unit, camera power supply, gyro sensor unit, gyro power supply, and instrumentation tape recorder. Output from the three video channels are stored on three tracks of the tape recorder, while a data track records basic timing information, line synchronizing signals and an arbitrary frame number which permits selection of data to be reproduced on film.

The ground station equipment consists of a magnetic tape reproducer and a color film recorder. The laboratory tests were performed with the camera operating directly into the color film recorder. Our discussion of system design and performance will generally ignore the tape interfaces until a description of the flight test program is given. Our general description of system operation will relate to the original intention of spacecraft operation, thereby leading to the evaluation of performance in terms of a space platform subsystem.

The operation of the MSIDC may be compared fairly realistically to mechanically scanned multi-band instruments, since the general output is similar. The similarity stops there, however, since the MSIDC is fully electronically scanned, with magnetic deflection fields moving an electron image across a sensing (electron image) plane in the same manner that an oscillating mirror would move an optical image across a sensing (optical image) plane. For each spectral band in the MSIDC we provide a color filter ahead of the photocathode and a separate sensing aperture and electron multiplier at the electron image plane. The number of spectral bands is limited by the practical restrictions of spacing of color filter strips and internal aperture and electron multiplier structures. The three bands selected proved to be no hindrance, and can be expanded to more channels in future systems.

The MSIDC camera would be mounted vertically in the spacecraft, with its scan axis orthogonal to the line of flight. The electronic scan therefore causes each aperture to sample a line of the earth's surface on each scan. This is illustrated in Figure 2-1. Transmissive filters are mounted ahead of a fiber optic Image Dissector Tube, with the optical scene focussed on the fiber optic surface. Only that spectral information transmitted by the selected filter reaches the photocathode in a given area. This area is then scanned by the sampling aperture for translation of the optical data to electronic signals. The selection of aperture size determines the ground elemental area being sampled at any instant, and the combination of sample size, spacecraft velocity, and swath width determine the scan rate required to generate a contiguous image. These factors are examined in greater detail in a later section.

As an electronically scanned system we recognize that the MSIDC has no moving parts. The instantaneous action of the photocathode makes shuttering unnecessary (sample time is approximately 2 microseconds) and all deflection is performed by magnetic fields. The wide

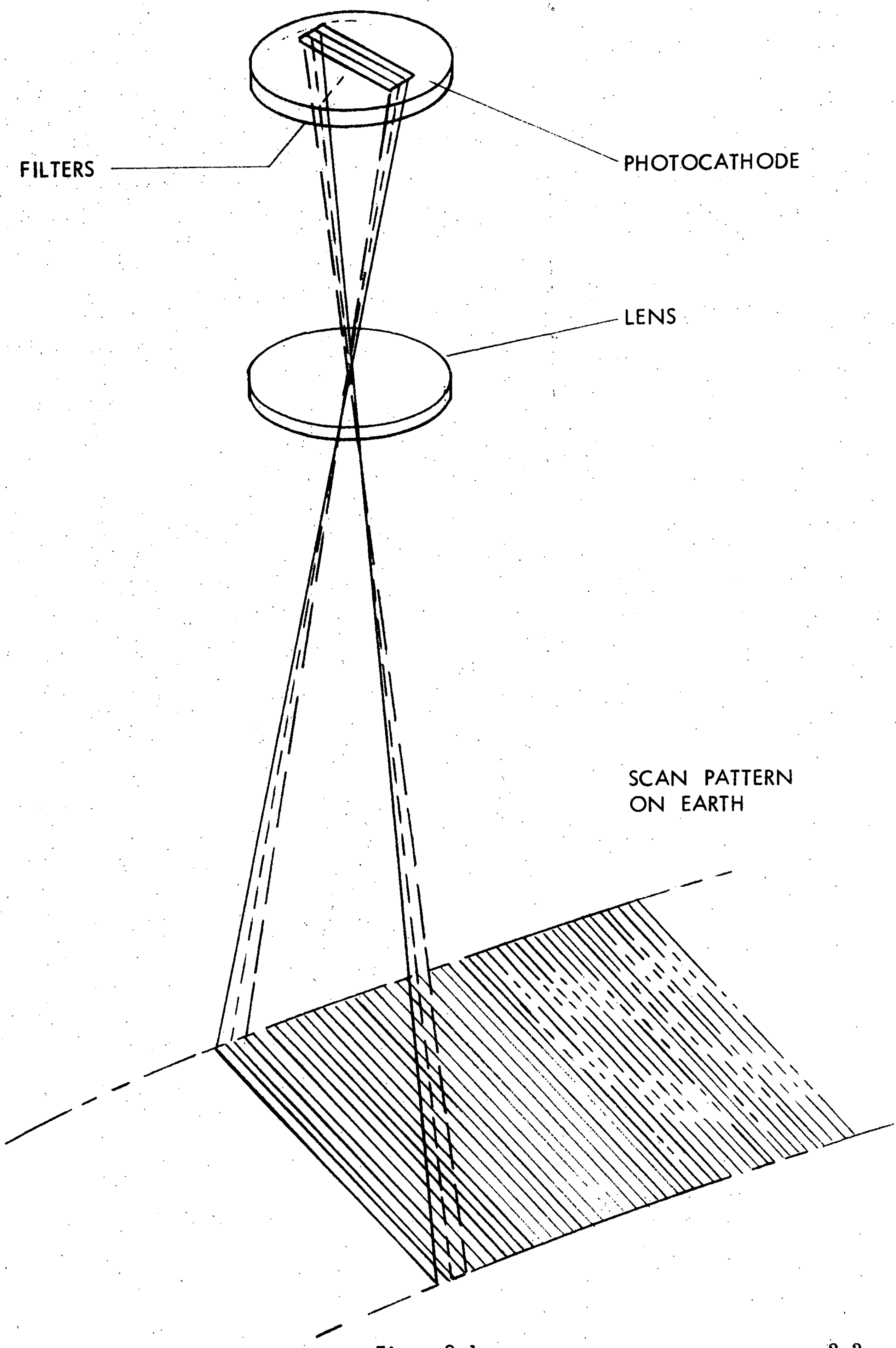

Figure 2-1

dynamic range of the MSIDC (13 $\sqrt{2}$ grey shades) makes an iris unnecessary, as was demonstrated in the early flights of the Nimbus camera system. One factor that must be considered in detail is the misregistration potentially caused by spacecraft motion during the time differential between line scans of a given spot on the earth. With present spacecraft stabilities on the order of 0.005°/sec. this error is less than one-third element. As demonstrated in the aircraft test program, a motion sensing gyro capable of detecting movements of 1 arc second could be added to the system to compensate for such instabilities, permitting the use of the MSIDC on less stable (and less costly) spacecraft.

2.2 Camera Unit

The multi-spectral system consists of two basic units. The camera unit and the color film reproducer. In the camera unit, we include the combination of optics, sensor tube, electronic circuitry and all power supplies that would be required for the airborne or spacecraft system. In this description, we will discuss the camera unit in a configuration as it now stands at the end of the program with the unit in aircraft flight status. A block diagram of the camera unit is shown in Figure 2-2 and shows the major components of the camera unit.

2.2.1 Time Base

A crystal oscillator operating at 24.25 MHz provides a constant frequency time base for all functions of the multi-spectral camera. Digital divider circuits reduce this basic timing signal to a number of basic frequencies, selectable by switch control. The digital switching capability permits a selection of frequency control that allows deflection of the

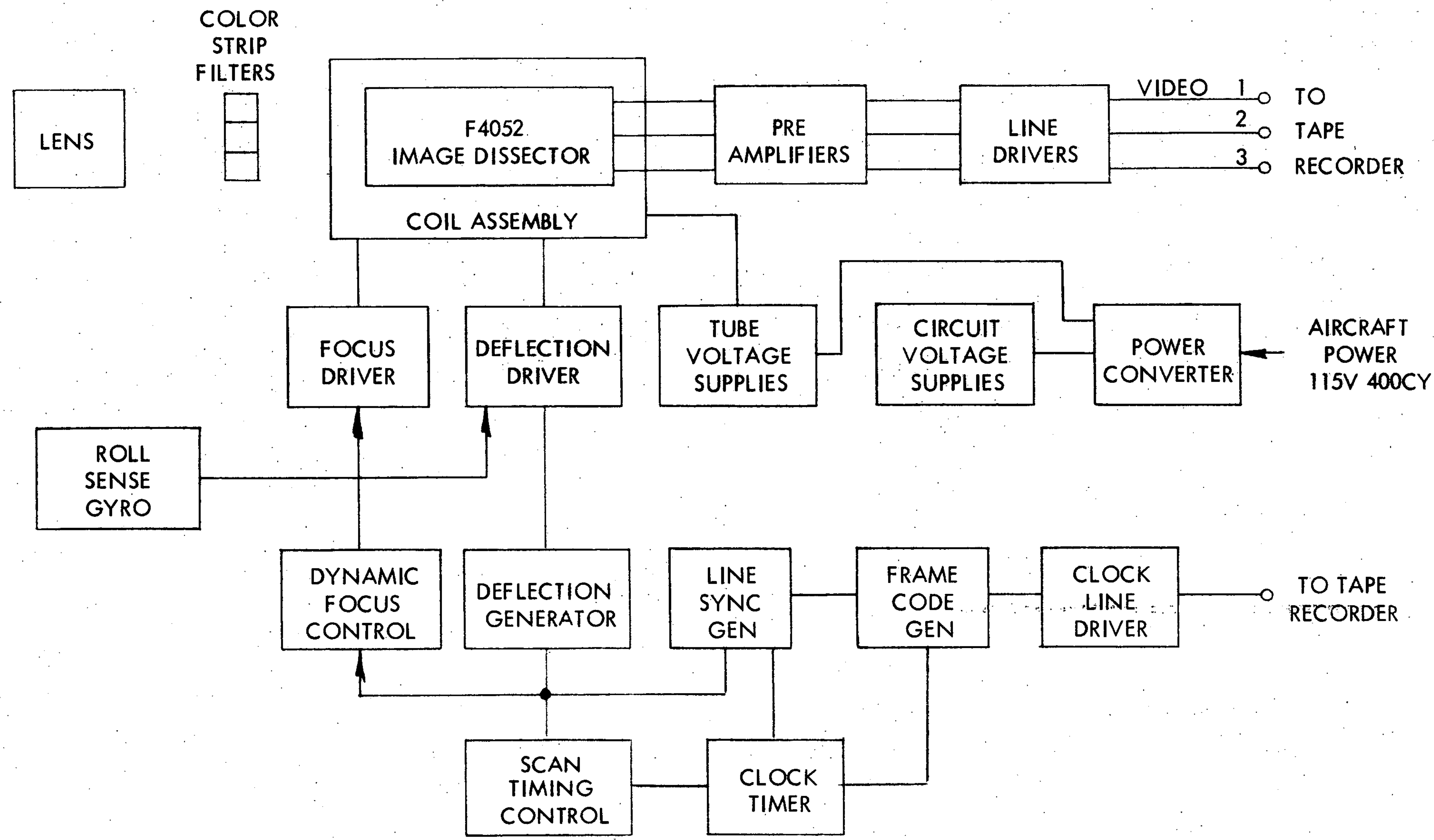

Figure 2-2. Multi-Spectral Camera Block Diagram

line scan over a very wide range from approximately four scans per second to 140 scans per second, maintaining the number of line elements per scan at a constant 6144. The counting system makes use of DTL logic and has been shown to be very precise and highly stable. The range of line scan rates is desirable in that it covers all requirements from low frequency scans for laboratory evaluation to the highest frequency requirement of the airborne application. Outputs from the time base generator are used to activate the line scan circuitry and to provide the synchronizing signals for generation of line synchronization and frame annotation codes. The basic elemental frequency waveform with these codes inserted are provided as a separate output from the camera unit and act as the synchronizing means for the reproducing of the imagery.

2.2.2 Deflection

A single set of deflection coils are used in the multi-spectral camera. The coils are driven from a feedback-type of current driver wherein the output current going through the deflection coil is compared to the input voltage waveform of the deflection driver. This input voltage waveform in turn is generated by a digital to analog converter acting from the time base signal and a highly linear digital to analog converter circuit. The deflection system is capable of direct current control such that a given step signal may be applied and the current in the deflection circuit will be held at that level. This has shown to be a useful technique in that individual step motions can be applied to the deflection circuitry for determination of system stability and image resolution. Since the normal operation of the system is with a continuing scan the stair step waveform generated by the digital to analog converter is smoothed to reduce the sharp variation from digital step to the next digital step. A highly stable and accurate waveform is therefore generated.

In addition to the ramp deflection signal, additional signals are generated to insure a highly accurate deflection characteristic. A dynamic signal is generated for the correction of S distortion at the extremities of the deflection waveform. This small correction is applied to the vertical deflection driver. The combination of a digital to analog conversion process and the application of the S distortion correction signal provides a highly linear deflection characteristic. This system has been very successful in its reliability and stability.

2.2.3 Focus

A focus current regulator is used to maintain a highly stable magnetic field for the image dissector tube. A focus current regulator provides approximately 290 milliamperes continuous current to the solenoidal focus coil. This is sufficient to provide a magnetic field which causes the electron image to be focussed at the second node. Under these conditions we have found less than 10% degradation in resolution at the edge of the image with respect to the center. In addition to the continuous DC current applied to the focus coil, a dynamic focus waveform source is included that has the capability of providing selected amounts of current for aiding or deterring the focus current at either edge of the image. This dynamic focus current adjustment is normally made only during the initial alignment of the camera system. We have found that once adjusted, the electrical focus of the camera seldom needs to be corrected.

2.2.4 Tube Voltage Supplies

The photocathode of the image dissector operates at approximately 2400 volts negative with respect to the output anode of the electron multiplier which is at ground potential. This high voltage is generated by a combination of two power supplies, each being an oscillator and converter type power supply operating at a frequency of about 7 KHz. The 2400 volts are generated by the addition of an 1800 volt and 600 volt supplies. The output of each is filtered by a two stage RC and LC filter network. The 2400 volts is applied to the photocathode which is the first element of the image section of the image dissector tube. The image section of the tube itself operates at 600 volts referenced to the photocathode potential. The 600 volt supply is isolated from the 1800 volt supply except at the output. A voltage detection network recognizes any variation in the 600 volt supply and feeds back a correction signal to the input oscillator voltage source, thereby assuring a constant image section voltage under all conditions of photocathode loading and any deviation in the high voltage supply. From the 1800 volt potential a series of resistive networks provide the voltages for each of the dynodes of the electron multiplier that follows the sensing apertures. The three dynodes of each stage of the electron multipliers are tied together for the three apertures, therefore a single voltage is supplied to the three dynodes immediately following the aperture and a voltage of 150 volts separates that dynode from the next dynode in the string. Again the three second dynodes are tied together and are connected to a common voltage point. This is continued for all of the ten dynodes in the electron multiplier assembly. A current of approximately 1 milliampere flows through this dynode string which is sufficiently high to prevent deviation of dynode voltages caused by electron currents in the dynodes themselves. The resistive divider for the dynodes are assembled in a potted module hermetically sealed to the base of the image dissector tube, such that only the 2400 volt, the 1800 volt, and the 0 voltage lines come from the tube to the power supplies. In addition, a signal lead from each anode is brought out for the video from each of the electron multiplier strings. The development of the high voltage supply and the floating regulated image section supply were performed as potential design approaches for space flight operation. They have shown great promise in these stability and regulation characteristics. In preparation for the aircraft flight, it was necessary to modify our laboratory breadboard supplies in order to improve the voltage breakdown characteristics under low pressure conditions. The generous use of solithane potting material and careful attention to connecting points and the high voltage leads were able to make the unit reliable under conditions of 60,000 foot operation. A design of the system for spaceflight use would have all of these components included in a package with complete encapsulation as was accomplished in previous space programs such that fully reliable operation could be obtained.

2.2.5 Video Amplifiers

From the three separate electron multiplier outputs we have individual low noise preamplifier modules with feedback to provide a wide dynamic range. The preamplifiers are adjusted for output relating to the photometric calibration of the input for each color channel. A video gain control is therefore included in each channel for this adjustment.

The operation of three closely spaced electron multipliers causes a slight amount of cross-talk between channels. In the physical assembly of the apertures and electron multiplier structures some electrons from the dynodes of one string tend to be picked up in the other dynode strings. This signal is typically less than 10% of the video from the initial dynode string. In order to compensate for this cross talk a series of cross coupled mixers are used to provide a negative video signal from channel 2 to channel 1 and to channel 3. This has reduced the effective cross talk to less than 1% and makes the effect of this characteristic negligible in the output of the camera systems. The three channels of video are provided on separate BNC connectors at the output of the camera unit. In addition to the control for normalizing the video otuputs a four level step function signal is inserted in the video near the output of the system. This four step gray level signal provides an internal test signal which permits adjustment of the image reproducing equipment so that when recording an image having unknown color content, the output from the system will faithfully reproduce the color characteristics of the scene.

2.2.6 Line Scan Synchronizing

As described earlier, the digital time base is derived from a master clock signal through a series of dividers from which a given line rate is selected by the operator before flight. Once this line rate is selected, a specific number of digital pulses are generated during each line interval. A counter system recognizes the beginning of each line interval and generates a string of five pulses having an amplitude 50% greater than the time base.

These pulses are then recognized in the reproducer unit and are able to precisely synchronize the scan of the film reproducing unit. The string of pulses (6,144 total) during each line scan are outputed on a fourth RF to the fourth track of the tape recorder. Since all apertures are affected by the same magnetic scan there needs to be only one line synchronizing signal and one set of time base pulses.

2.2.7 Frame Annotation

On the same pulse string and occurring during the horizontal retrace interval a frame code is included in the pulse train on the fourth output track. The frame annotation signal is a binary coded decimal signal that follows the line synchronizing signal. The difference between the time interval when one aperture use a specific point in an image to the time that another aperture use that same point in an image is known, since it is a fixed physical relationship there is a specific number of line scans in this interval. The frame annotation signal is applied to each line scan and occurs at a given point in time. Since the scanning of the camera is continuous, there are no true frames therefore an arbitrary number of 2048 line scans has been selected at which time the frame annotation number increases by 1. This means that in an image that might include 3000 lines of information, the beginning of a frame might occur at 2/3 of a picture interval, permitting copy of overlapping scenes. The frame annotation begins at the time that the camera is turned on. This means that the frame number itself is an accurate indication of elapsed time, and may be used to determine scene location if the aircraft flight plan is known. The pilot may elect to turn off the tape recorder over an area of poor visibility or undesirable targets but the camera and its frame counter continue to run. When the tape recorder is again turned on the frame annotation may indicate a number considerably higher than the last recorded frame. This is not detrimental to operation and in fact is often useful in the recognition of the time of exposure of a given area image. During film reproduction, the reproducer unit starts at the beginning of a frame and continues until the film carriage is stopped. This system has been very successful and contributed to the generation of good output from the system.

2.2.8 Roll Sense Gyro

A highly useful and successful addition to the multi-spectral camera was provided by NASA's gyro unit which sensed the motion of the aircraft during camera operation. The output from the gyro unit was fed to the input to the horizontal deflection amplifier such that roll of the aircraft was immediately compensated for by an opposite deflection of the magnetic field. The image as seen at the aperture plate moves from side to side keeping the center of the image always related to the local vertical. It may be recognized that under conditions of extreme roll, that the edge of the optical image on the photocathode might be detected in the scanning of the electron image. This is apparent in some of our imagery, however, in general with the aircraft that was available, the roll seldom exceeded 2 degrees and did not cause this characteristic. One of the characteristics of the roll gyro is an automatic caging cycle such that when the gyro senses an offset of one degree that it automatically returns to a centered position. In some of the imagery this occurred at a time when an important target was in the scene. A different design having a drift correction signal will reduce this effect in the future and permit continuous image generation. As an experimental system this roll sense gyro and the automatic motion stabilization were highly successful and indicate a very useful tool for both aircraft and spacecraft use. The particular unit supplied by NASA is capable of sensing motions of 1 second of arc of the camera system. Therefore, it is applicable even to a satellite situation where the roll of the satellite could be corrected.

2.2.9 Optics

The lens for spacecraft application requires 8.68 inch focal length, a low f number (T 1.2 assumed), and full color spectral response.

The lens procured for the evaluation program was not intended to be fully useful for a satellite type operation or even necessarily capable of fully exercising the image dissector camera. A high quality lens from Bendix Optical Division, model 502, having 4 inch focal length and an aperture of f.95 was obtained. This lens is corrected for spectral response from 400 to 900 nanometers and was used for much of the laboratory testing and for the flight test. This lens had many of the features desired, however it was not designed for the width of image plane that we had with the image dissector camera. The vignetting from the lens causes a reduction of light input of over 50% at the edges of our scan. This was very apparent in the flight tests and caused considerable difficulty in trying to match the color content of imagery from the several channels. In the reproducing of the final imagery, as shown in the early section, a dynamic video gain control was included in each video channel such that shading effect was neutralized, however recognizing that the noise content is higher at the picture edges than at the center, and that the contrast of the imagery is reduced. This would not occur with an optic system designed to a full camera specification. The use of a low f number optic system requires special care and focus adjustment and then a compensation for a difference in air density in the laboratory compared to that in aircraft high altitude, and certainly at spacecraft altitudes. In our case, we calculated this difference and adjusted the optics mount to the calculated position when the system was installed in the aircraft. The results from the combined system indicated that there was no resolution change in the flight system.

2.2.10 Spectral Filters

The filters used in the evaluation system were ordered to match rather closely the spectral ranges of the return beam vidicon program for the Earth Resources Satellite. An assembly contained three strip filters in the spectral band of 475 to 580, 580 to 680, and 690 to 930 nanometers. These filters are deposited filters on glass substrate. The first filter in line in the direction of flight motion is the low band (green) filter. The second, or center filter, is the central band (red) and the lower filter is the far red band filter. Since the aperture separation in the image dissector tube is 0.083 inches the central filter was made 0.085 inches by 1.75 inches, while the other two filters are 0.75 inches by 1.75 inches with masking to prevent any transmission outside an area 0.25 inches wide. The filter surface is mounted on a glass substrate which is held approximately 0.020 inches away from the fiber optic faceplate of the image dissector tube. The characteristics of the three filters are shown in Figure 2-3. The efficiency of these filters and the stability indicate successful techniques and would likely be the method used in the space application. A second set of filters were procured and used for laboratory tests in the normal visible spectral bands centered on 450, 550 and 650 nanometers. Imagery from these filters are comparable to normal color photography. There were no flight tests made with this filter combination.

2.2.11 Sensor Tube

The sensor tube used in the multi-spectral camera is an ITT F4082 with fiber optic faceplate and S25 photocathode and three apertures. The tube is 2.25 inches diameter and 11.75 inches long, and is shown in Figure 2-4. The tube serial No. 037001 was used in the final evaluation tests in the laboratory and was used in the flight testing from the aircraft. An unfortunate accident occurred when after the first flight test the camera was shipped back to ITT for modification and the tube was damaged in the process. The accelerating screen support ring had been dislodged, a laser welding process was successfully used to remount the ring. However, when this occurred, the laser energy apparently caused a localized degradation of red response. This effect is noted in the final flight test imagery. The tube is mounted firmly in the camera unit, with an encapsulated divider assembly attached to the base of the tube. The deflection and focus coil assembly mount solidly to a base plate which is the mounting plate for the camera unit. The aperture size in the sensor tube is 15 micron diameter or 0.0006 inches. The three apertures are spaced

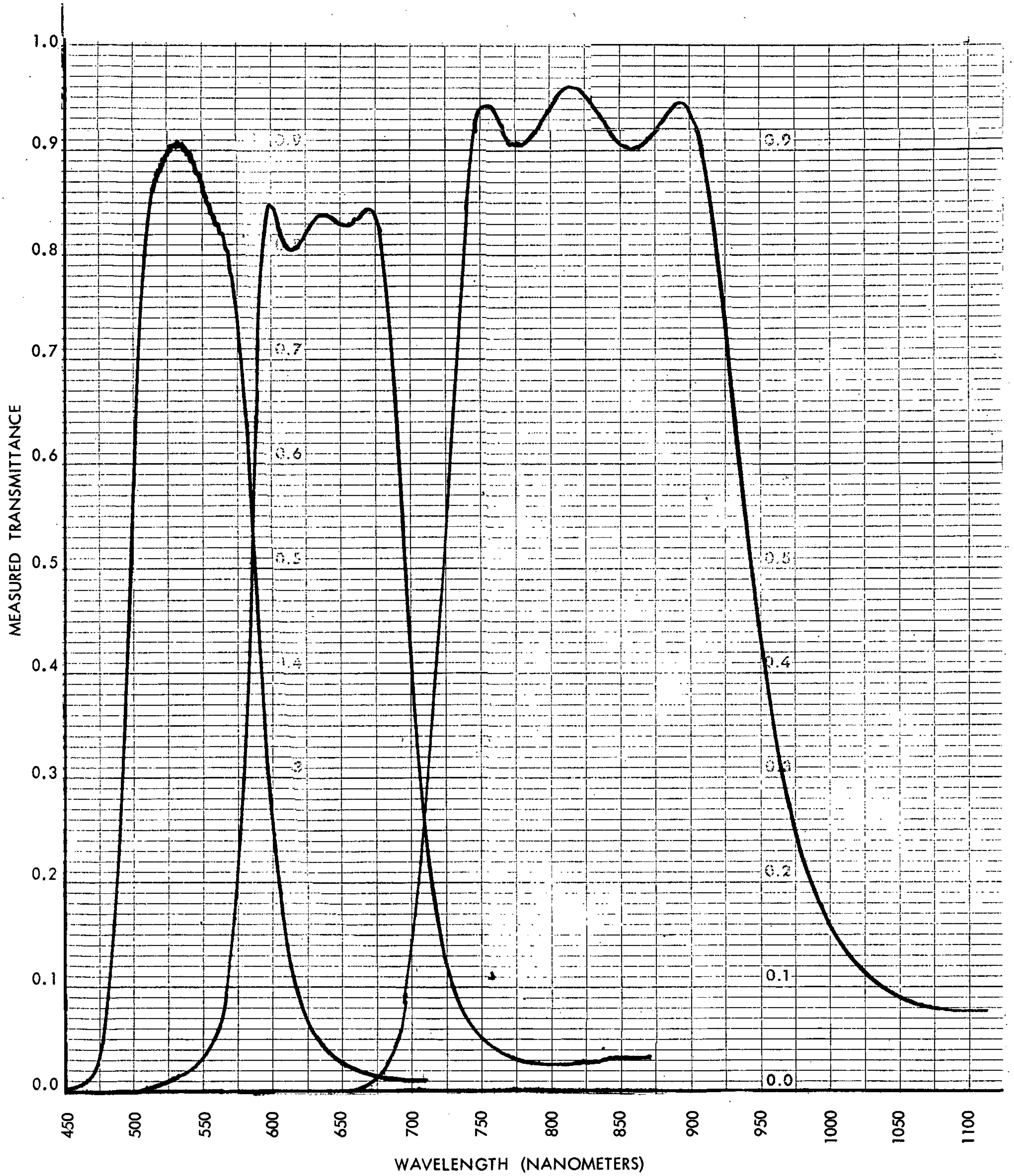

Figure 2-3. MSIDCS SPECTRAL FILTERS

Figure 2-4. Multi-Aperture Vidissector

0.083 inches apart and are in front of a triple electron multiplier assembly having bucket type dynodes which are 0.125 inches across. It is evident then that with the center aperture in the center of the first dynode that the other two apertures are slightly offcentered in their respective dynodes. This has not caused a significant problem in signal shading. It is anticipated that future tube designs will have changes or improvements to reduce signal crosstalk between dynode strings and possible different configurations in terms of aperture separation.

2.2.12 Configuration

The camera unit is contained within a box 9 x 9 x 18 inches not including the lens which is approximately 6 inches diameter and 6 inches long. In addition brackets were added at the rear of the camera unit to mount the gyro assembly making a total package configuration 26.5 inches long. The weight of the camera unit itself is approximately 55 lbs. In addition to the former unit, a camera control unit contains the power supplies and the oscillator time base unit. A second container includes the power supply and amplifiers for the gyro unit. The system interconnection from the gyro unit goes back to the camera control unit where the gyro signal is inserted in the deflection signal as applied to the deflection drivers. The weight of the complete airborne system is 95 pounds and consumes approximately 165 watts from a 120 volt, 60 to 400 cycle aircraft supply.

2.3 Color Film Recording Unit

A laboratory film recording unit has the means of reproducing color separation or multi-color separation or multi-color positives or negatives for evaluating the system.

This piece of special test equipment provides imagery which demonstrates the resolution, color fidelity, and registration of the system. The color video data from the camera unit and the timing sync line one processed to apply the video to a high resolution line scan cathode ray tube. The CRT is line scanned sequentially for the three color inputs. The vertical position of the line scan is offset to a distance equivalent to the separation of the apertures in the camera tube. Gelatin color filters are inserted in front of a film plane where each of the lines will be focussed on a color film. The color film in its mount is moved vertically past the line position. Figure 2-5 is a block diagram of the color film recorder unit.

2.3.1 CRT Recording System

The video from any single color channel of the camera (or from a track of the tape recorder) is applied through a single video amplifier to a high resolution CRT (Litton L4238P24R). This CRT has an extinction resolution of over 4000 TV lines, a P24 phosphor and a wide dynamic range. The video signal applied to the CRT is synchronized with the line scan controlled by the input timing pulses and line sync signals. The light output from the phosphor is focussed through color filters to the film plane. A photomultiplier tube gathers light from the face of the CRT and generates a video signal which is compared to that being applied at the input to the CRT. This feedback system insures an accurate contrast range and linearity of reproduction over the complete scan on the CRT and in fact greatly reduces the effect of blemishes and shading in the CRT.

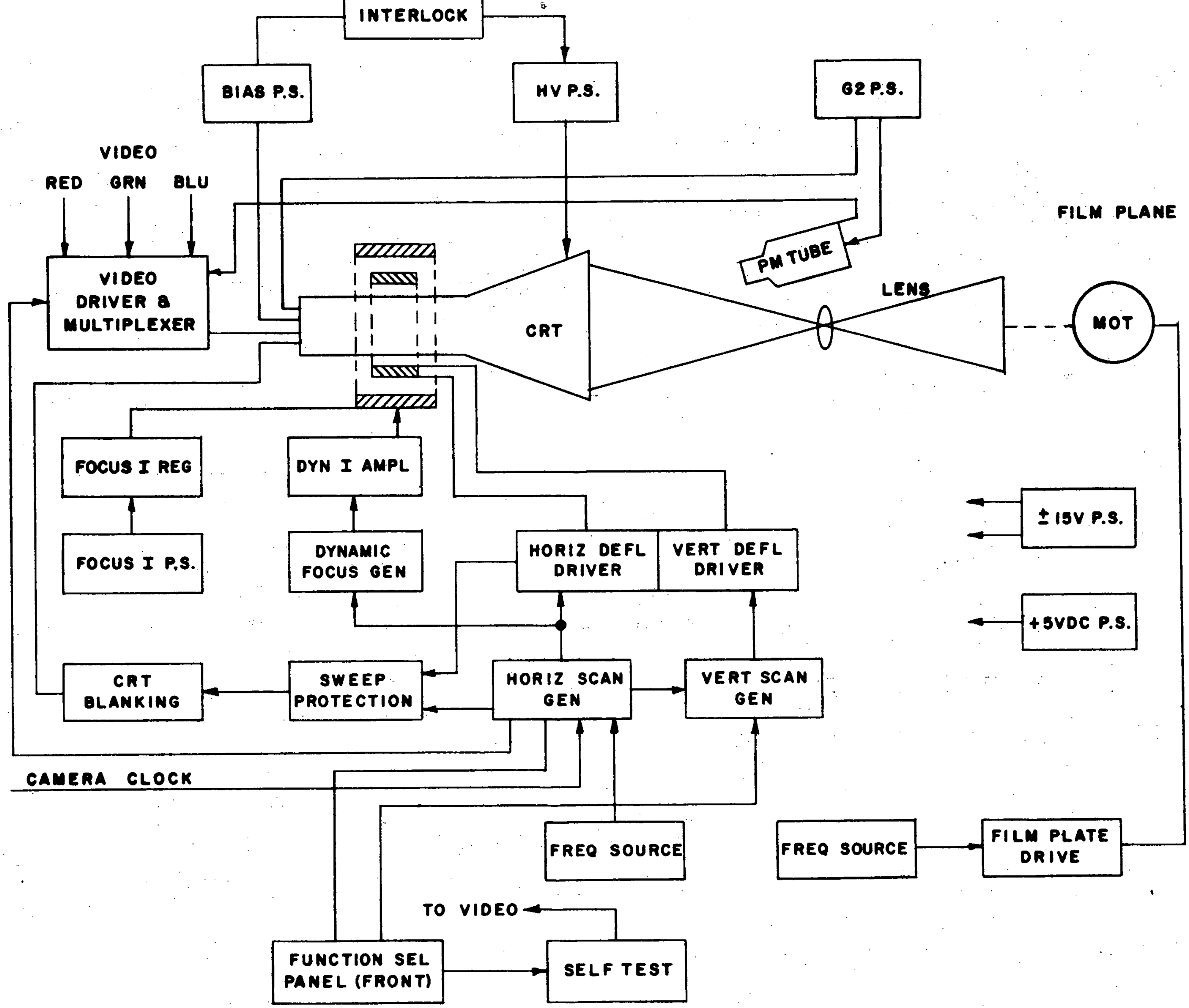

Figure 2-5. Block Diagram of Color Film Recorder Unit

2.3.2 Deflection Registration

The timing signals received from the camera unit are decoded to generate deflection waveforms. The timing pulses are applied through digital to analog converters and generate a deflection in the CRT which is identical to that used by the camera unit. Corrective circuits are included in the deflection circuitry to offset any effects of pincushion distortion at the edges of the scan. The selection of color channel input, which is a manual control, determines which of three vertical positions the CRT line scan will take. The offset is a set deflection voltage, however it has a separate correction signal for each of the three color scan positions. In order to record three color imagery it is therefore necessary to record an image in one color, replay the tape or rerun the test target past the camera and record the other images in sequence. The system operates equally well in line sequential mode and was used in this mode for many lab tests.

2.3.3 Film Holder Assembly

Since the CRT is fixed in position and line scans through color filters to a film plane it is necessary to move the film vertically past these positions in order to make a complete image record. The film motion assembly is a highly precise unit with a worm gear assembly driven by a stepper motor. The stepper motor itself is in turn driven from the oscillator or the timing signal that controls the camera scan. Therefore both the film motion and the CRT deflection are in perfect synchronism. The film assembly can be moved and reset for the start of a second overlay recording to an accuracy of less than 1 resolution element, permitting the recording of three colors.

2.3.4 Timing System

The photo recording system is a slave to the incoming timing signal. The frame annotation signal is recognized by a preset code that is set up by thumbwheel switches. The beginning of a new frame number will cause the film motion assembly to start and will continue the frame and line synchronized image generation until a stop signal is recognized from the film motion assembly.

2.3.5 Self Test Features

Included in the color film recording unit are self test features which permit the application of square waves or gray scale patterns to the CRT, such that the linearity of any one color channel may be tested and the registration of all three colors may be tested and demonstrated. From this it has been shown that the system is capable of a resolution of 4000 TV Lines, and a color registration of 1 part in 2000.

2.3.6 Configuration

The color film recording unit is mounted in a self contained double size rack with the CRT mounted horizontally on top of the cabinet and the film assembly open where a film pack may be inserted permitting the use of a number of different types of film.

See Figure 1-2.

3.0 SYSTEM EVALUATION, ANALYTICAL

A major effort during the development of the multi-spectral camera was the analytical study of a system configuration that might meet the requirements of the Imaging System for the Earth Resources Technology Satellite. In the application of the image dissector camera there are enough variables that a given selection of system components and operating mode may be found optimum for a given set of requirements. Figure 3-1 depicts the major system components and the major considerations for each. The system baseline is given in Table 3-1.

The approach used by ITT to determine the ability to meet the base line requirements was to establish the basis of detection of small, low contrast elements. The series of studies therefore include a definition of contrast, the detection of low contrast scene elements in the presence of modulation characteristics of optics and sensor tube, and the effects of noise in the system.

3.1 Optics

The use of a single lens for the multi-spectral system will permit the application of a large aperture lens, with a special requirement for high resolution across the image surface of 1.75 inches (45 mm), and broad spectral response (480 to 950 n meters). Proposals from several leading optical companies were received. A selected lens has the resolution (MTF) response shown in Figure 3-2. The lens aperture of f/1 to T/1.2 is predicted from the same proposal.

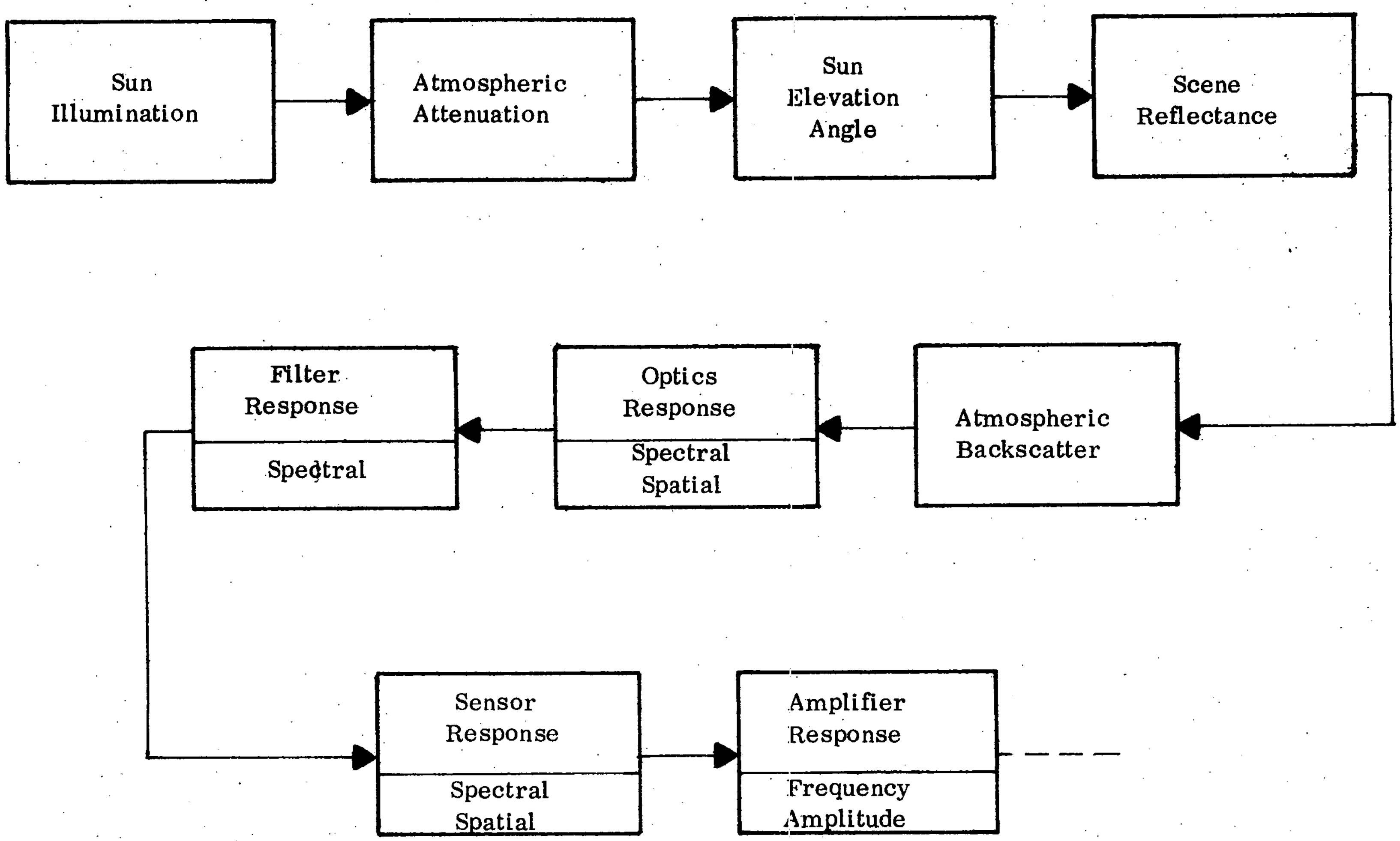

Figure 3-1. System Major Variables

Table 3-1. System Baseline

Spacecraft Altitude	496 n miles
Ground Velocity	21.2 x 10^3 ft/sec
Field of View	100 nautical miles
Solar Zenith Angle	60^o
Atmospheric Attenuation	3 air masses
Channel Radiance per spectral band	
470 to 570 nanometers	0.85 mv/cm^2/ster
580 to 680	0.85
690 to 830	1.36
Scene Contrast Ratios	6.3 to 1, 2 to 1, 1.4 to 1
Detectable Ground Detail	Smallest Possible
Minimum Acceptable Signal to Noise Ratio	1.8

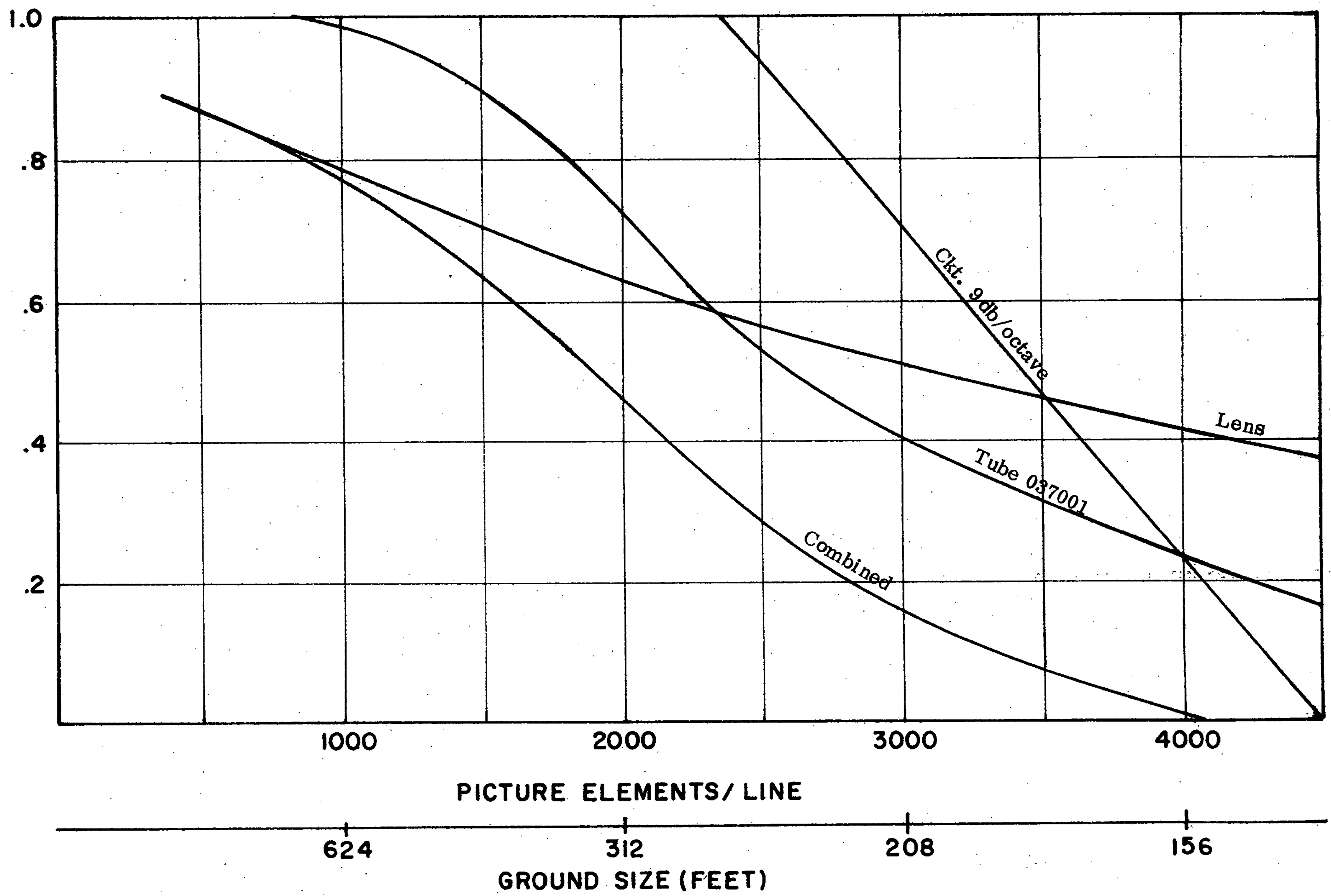

Figure 3-2. System Component Spectral Response

3.2 Spectral Filters

The use of three strip color filters ahead of the fiber optic tube faceplate is assumed for the flight program. Transmissive type filters having half amplitude pass bands from 475-575, 580-680, and 690-830 nanometers are considered. The spectral response characteristics of the filters are assumed squarewave filters with 0.85 transmission. In later procurement we found these to be conservative numbers, with available filters having higher transmission than these estimates.

3.3 Sensor Tube

The image dissector tube is the ITT type F4082 with three identical round sampling apertures spaced uniformly in a line orthogonal to the scan direction. The size of aperture will be discussed later as one variable in the system. The photocathode is an S25 photocathode having a spectral response as shown in Figure 3-3.

The resolution of the tube is determined by aperture size, but we cannot assume an ideal condition. A measurement of resolution for the tube used in the laboratory model camera is shown in Figure 3-2. This is the response from a tube having sampling apertures 15 microns diameter (0.0006 inches). The measured response of this tube is used in the calculations that follow.

3.4 Amplifier Response

The amplifier for image dissector cameras seldom contribute noise to the system, since the gain of the photomultiplier is set to maintain the low light level signal above amplifier

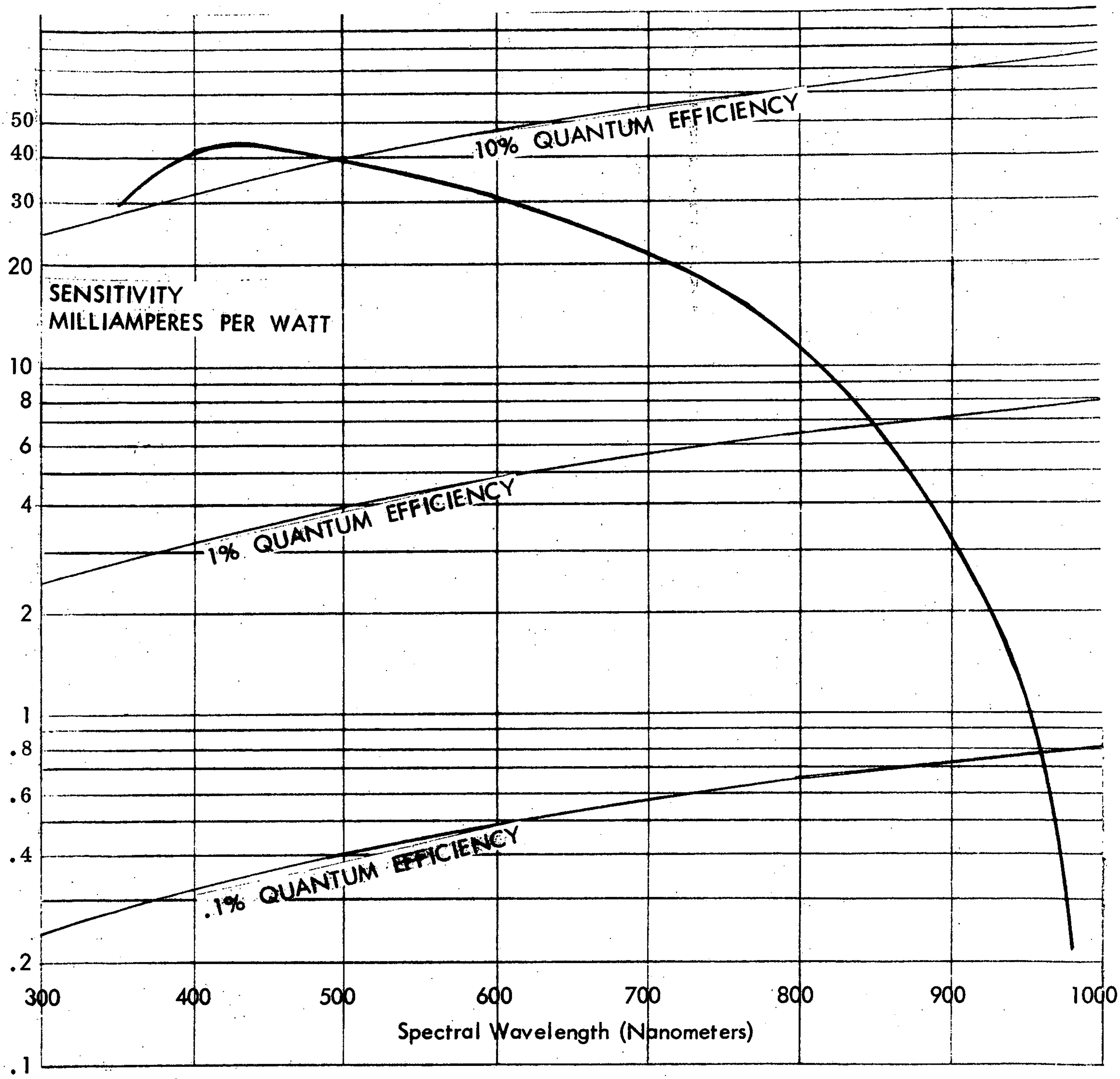

Figure 3-3. Photocathode Response

input noise levels. The amplifier frequency response will have an effect on performance, since the desired bandpass is one which effectively passes the highest signal frequency content but does not contribute spurious noise beyond that point. We assume a video amplifier with a 9 db per octave drop and a 3 db loss at the highest frequency of interest. This is considered in calculating the true MTF of scene elements. A system MTF may be determined then using the amplifier, optics, and tube responses of the system. The combined response is shown in Figure 3-2.

3.5 Signal to Noise Predictions

The output of the system with reference to the system baseline can best be described as a signal-to-noise ratio. This measurement for the image dissector is the ratio of the signal level from a given input radiance to the rms value of the noise present in the signal channel at that time. In the absence of any background noise effects the noise level will increase as the signal increases at a square root relationship. Three sources of background noise will be considered negligible, these being thermal noise from the photocathode, leakage currents at the anode, and amplifier noise. The electron multipliers add noise which will be considered, with a relationship to the dynode gain. A multiplying factor of 0.89 will be used to account for this noise source. The effect of atmospheric backscatter will be considered in the calculations when the effects of contrast ratio are introduced.

A low frequency (large area) signal to noise ratio may be calculated from the data now available. Originating with the sun's irradiance outside the earth's atmosphere Ho, we can progress through three earth masses (for a sun elevation angle of 60^{o}) and arrive at an irradiance at the sensor photocathode. This is tabulated in Table 3-2 for each 10 n meter increment, where Ho is the seen irradiance outside the atmosphere, H_{3m} is the equivalent irradiance after reduction by atmospheric attenuation. The radiance of the earth is shown in the fifth column. Using this radiance we can determine the irradiance on the photocathode and calculate the current emitted from the photocathode. The intermediate steps include the attenuation of the lens (T1.2) and the spectral filter transmission factor (0.85) which are assumed constant in the band of interest. The spectral response of the photocathode is shown, and the resulting photocathode current density is given in the final column.

It is interesting to note that the integrated radiance from the earth as calculated here for the three bands (1.47, 1.54 and 1.83) are considerably different than the numbers supplied by NASA (0.85, 0.85, 1.36) as given in Table 3-1.

The NASA supplied numbers are considered realistic values for surface reflectances of 0.25, 0.30, and 0.50 and some atmospheric backscatter. Although somewhat arbitrary, these values will be used as our baseline for radiance in each channel. This results in a typical earth scene reflectance, low frequency photocathode current density of 14.8, 13,3, and 10.3 microamperes per square centimeter.

Signal to noise ratio for an image dissector may be calculated from the current density with an attenuation factor for accelerating screen mesh transmission, aperture area, and sampling time interval. A factor for dynode noise must be included, and a factor for translating current to number of electrons completes the equation.

Table 3-2. Sun Source to Photocathode Response

Wavelength (Nanometers)	H_o (w/m^2)	(Transmission) (Per Atmosphere)	H_{3m} (w/m^2)	Radiance (mw/cm^2/st)	(Photocathode) Sensitivity (Ma/watt)	Current (μA/cm^2)
470	21.5	0.728	8.30	0.132	40.8	2.496
480	20.7	0.755	8.91	0.142	40.2	2.646
490	20.6	0.766	9.27	0.148	39.6	2.717
500	19.6	0.789	9.63	0.153	39.0	2.766
510	19.3	0.792	9.58	0.152	38.0	2.677
520	19.4	0.787	9.44	0.150	37.2	2.586
530	19.8	0.775	9.22	0.147	36.6	2.494
540	19.7	0.780	9.36	0.149	35.8	2.472
550	19.3	0.785	9.34	0.149	35.0	2.417
560	19.0	0.788	9.30	0.148	34.2	2.346
	198.9		92.35	1.47	376.4	25.7
580	19.0	0.785	9.18	0.146	32.6	2.21
590	18.8	0.785	9.11	0.145	31.8	2.17
600	17.9	0.808	9.45	0.150	31.0	2.16
610	17.6	0.815	9.54	0.152	30.0	2.11
620	17.2	0.825	9.65	0.154	29.0	2.06
630	16.8	0.838	9.89	0.157	28.0	2.04
640	16.4	0.848	10.00	0.159	27.0	1.99
650	16.1	0.852	9.97	0.159	26.0	1.91
660	15.7	0.863	10.10	0.161	25.0	1.86
670	15.3	0.871	10.10	0.161	24.2	1.80
	170.8		96.99	1.54	284.2	20.3

Table 3-2. (Continued)

Wavelength (Nanometers)	H_o (w/m^2)	(Transmission)	H_{3m} (w/m^2)	Radiance ($mw/cm^2/st$)	Sensitivity (Ma/watt)	Photocathode ($\mu A/cm^2$)
690	14.6	0.819	8.03	0.128	22.8	1.30
700	14.3	0.881	9.78	0.156	22.0	1.59
710	14.0	0.874	9.35	0.149	21.0	1.45
720	13.6	0.781	6.48	0.103	20.0	0.96
730	13.2	0.857	8.31	0.132	19.0	1.16
740	12.9	0.898	9.34	0.149	18.0	1.24
750	12.6	0.831	7.23	0.115	17.0	0.91
760	12.3	0.681	3.88	0.062	16.0	0.46
770	12.0	0.899	8.72	0.139	15.0	0.97
780	11.6	0.886	8.06	0.128	14.0	0.83
790	11.4	0.898	8.23	0.131	13.0	0.79
800	11.1	0.880	7.57	0.120	12.0	0.67
810	10.8	0.805	5.64	0.09	10.9	0.45
820	10.6	0.869	6.95	0.111	9.8	0.50
830	10.4	0.909	7.82	0.124	8.7	0.51
	185.4		115.42	1.83	238.5	13.8
840	10.2	0.918	7.89	0.123	7.6	0.44
850	9.92	0.920	7.73	0.123	6.5	0.37
860	9.69	0.914	7.40	0.118	5.7	0.31
870	9.47	0.919	7.35	0.117	5.1	0.28
880	9.26	0.812	4.95	0.079	4.5	0.35
890	9.06	0.758	3.94	0.063	3.8	0.110
900	8.85	0.736	3.53	0.056	3.2	0.083
910	8.66	0.632	2.40	0.038	2.76	0.049
920	8.47	0.554	1.44	0.029	2.32	0.025
930	8.29	0.453	0.77	0.012	1.88	0.011
940	8.12	0.587	1.64	0.026	1.44	0.017
950	7.95	0.785	3.85	0.061	1.0	0.030
960	7.78	0.863	5.00	0.080	0.8	0.030
970	7.62	0.909	5.78	0.090	0.6	0.025
980	7.47	0.933	6.06	0.096	0.4	0.018
990	7.32	0.935	5.98	0.095	0.2	0.008
	138.13		75.66	3.84		22.9

$$(S/N)_o = \left[\frac{J_K K_a t}{e} \frac{(G-1)}{G} \right]^{1/2}$$

where J_K = photocathode current density, amperes/cm^2

K = mesh transmission, typically 0.6

a = aperture area, cm^2

t = sampling time interval, seconds

G = dynode gain

e = electron charge, 1.6×10^{-19}

$(S/N)_o$ = peak signal to noise ratio (high contrast)

For a system having 208 ft. ground resolution, the sample time per element is 2.91 microseconds.

The signal to noise ratio for large area high contrast images is therefore:

Band 1	470 - 570 n meters	S/N =	15.3 or	23.6 db
2	580 - 680 n meters		13.5	22.6 db
3	690 - 830 n meters		12.8	22.1 db

Table 3-3 indicates the calculated current densities and signal-to-noise ratio for each of the conditions and presents an optional third channel which makes use of the extended red response of the S25 photocathode.

Table 3-3. Predicted Large Area Signal Response

Flight Model Predicted J_K and Peak S/N

Channel	Spectral Band (Nanometers)	Scene	Radiance ($Mw/cm^2/st$)	Photocathode Current Density, J_K ($\mu a/cm^2$)	S/N Ratio	S/N Db
1	470 - 570	100% Reflectance No backscatter	1.47	25.7	20.2	26.0
		25% Reflectance + Backscatter	0.85*	14.8	15.3	23.7
2	580 - 680	100% Reflectance No Backscatter	1.52	20.2	18.0	25.1
		30% Reflectance + Backscatter	0.85*	11.3	13.5	22.6
3	680 - 830	100% Reflectance No Backscatter	1.83	13.8	14.8	23.4
		50% Reflectance + Backscatter	1.36*	10.3	12.8	22.1
3'	680 - 990	100% Reflectance No Backscatter	3.04	22.9	19.1	25.6
		50% Reflectance + Backscatter	2.26	17.1	16.5	24.4

* NASA Supplied

3.6 Contrast Considerations

The previous description of sensitivity used a NASA baseline of earth illumination that was thought to be typical maximum scene reflectance and a reasonable amount of atmospheric backscatter. Although these numbers may not prove accurate (our experience from aircraft flight indicates much less backscatter), we will use these radiance levels as if they are the result of 100% contrast targets.

Since the noise level of the image dissector is related to signal level, the noise consideration for scenes of low contrast become complicated. In a low frequency signal of amplitude A, the noise is related to $\sqrt{A}$, hence the signal to noise is $A/\sqrt{A} = \sqrt{A}$. If the background level is A/C where C is the contrast ratio, the background noise is related to $\sqrt{A/C}$. Now if the signal shifts from A to A/C on a cyclic basis (square wave of equal duration) the average noise becomes

$$n = \frac{\sqrt{A} + \sqrt{A/C}}{2} = \frac{\sqrt{A}}{2} \left(\frac{\sqrt{C} + 1}{\sqrt{C}} \right)$$

The signal itself is $(A - A/C)$ or $\frac{A\,(C-1)}{C}$

For low frequency, cyclic variation of the signal we can relate signal to noise ratio to contrast.

$$\left(\frac{S}{N}\right)_C = \left(\frac{S}{N}\right)_O \frac{2}{\sqrt{C}} \frac{(C-1)}{(\sqrt{C}+1)}$$

where $(S/N)_O$ is the high contrast signal to noise ratio as described in Section 3.4.

We can now tabulate the low frequency signal-to-noise ratios for the baseline contrast numbers of 6.3, 2.0, 1.4 for the three channels,

Contrast	Band 1	Band 2	Band 3	
Steady State	15.3	13.5	12.8	signal to noise in signal
6.3	18.2	16.2	15.3	pk/pk signal to ave noise
2.0	9.0	7.9	7.5	pk/pk signal to ave noise
1.4	4.5	4.0	3.8	pk/pk signal to ave noise

Note that for cyclic signals of relatively high contrast (6.3) the signal-to-noise ratio is higher than for the steady state case. This is a characteristic of the image dissector with its steadily decreasing noise at low signal levels, rather than a continuous background noise that would need to be added to all levels of signal, as in the case of the vidicon. This potential gain of 2 in signal-to-noise ratio suggests that any filter combination that improves contrast may improve signal to noise ratio.

3.7 MTF Considerations

The factors of optics, sensor, and amplifier fall off as a function of spatial frequency may now be considered. The chart of Figure 3-2 gives the anticipated percent modulation with reference to TV Lines on the scan, and to ground resolution elements for the spacecraft system.

The result of increasing spatial frequency is shown in Figure 3-4, where the output signal is a modulation envelope that converges on a grey level that is the sum of background

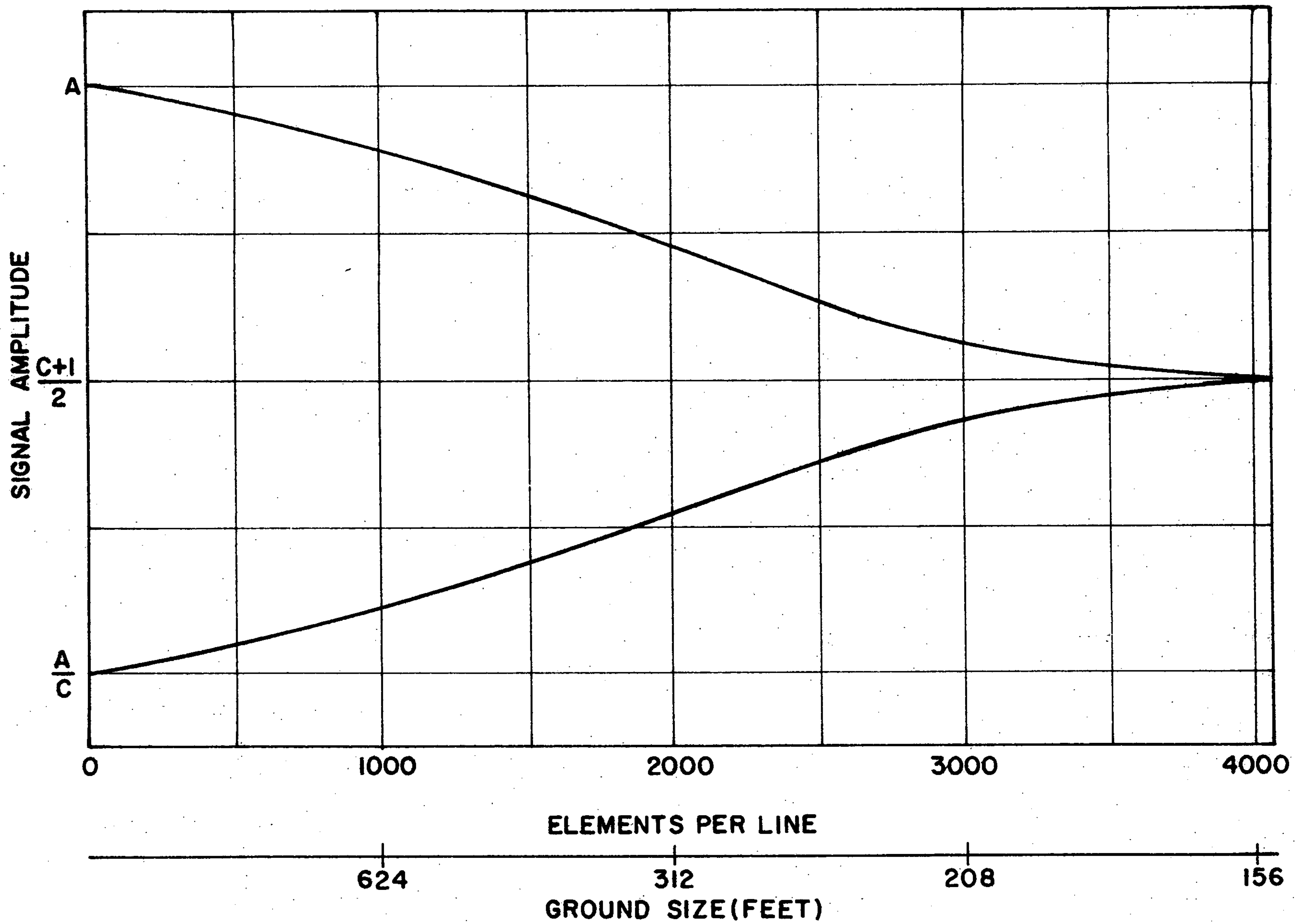

Figure 3-4. Video Modulation Envelope

(A/C) and the average signal 1/2 (A - A/C), or A (1/C + 1/2 - 1/2C), which is A $\left(\frac{C+1}{2C}\right)$ and at low MTF approaches this value. The signal-to-noise ratio then becomes:

$$(S/N)_f = (S/N)_o \quad MTF \frac{\left(\frac{C-1}{C}\right)}{\sqrt{\frac{C+1}{2C}}}$$

3.8 Limiting Resolution

The factors are all available to determine the spatial frequency for a given signal to noise as a function of radiance, system, and detection factors. A limiting signal to noise level of 1.8 has been given as a realistic minimum figure. Using this number as $(S/N)_f$ we can determine the MTF required, and from our chart (Figure 3-2) determine the related spatial frequency. The tabulation is given in Table 3-4.

This chart indicates that in the region of interest at a contrast ratio of 2:1 the system is capable of resolving ground targets of approximately 200 feet, and that the resolution of the three spectral bands are nearly equal.

3.9 Aperture Size Optimization

An early study in the program investigated the relationship of aperture size (instantaneous field of view) to detectability of very low contrast scenes. At that time, a supposedly realistic set of figures were assumed for contrast of typical crops and background. These were:

Table 3-4 Estimated Space Camera Response

Spectral Band (nanometers)	Peak S/N Ratio $(S/N)_p$	C = 6.3 Required Response	C = 6.3 Elements Line	C = 6.3 feet	C = 2.0 Required Response	C = 2.0 Elements Line	C = 2.0 feet	C = 1.4 Required Response	C = 1.4 Elements Line	C = 1.4 feet
470 - 570	15.3	0.11	3175	191	0.20	2730	222	0.38	2220	274
575 - 680	13.5	0.12	3100	196	0.23	2625	232	0.40	2175	280
690 - 830	12.8	0.13	3075	199	0.24	2580	237	0.56	1725	352
690 - 930	16.5	0.10	3240	188	0.19	2775	219	0.36	2275	267

	Band 1		Band 2		Band 3	
Crop	Reflectance,	Ratio	Reflectance,	Ratio	Reflectance,	Ratio
Barley	0.121	1.70	0.1512	1.70	0.201	1.29
Loam	0.071		0.0889		0.155	
Healthy Barley	0.099	1.19	0.1143	1.00	0.1806	1.15
Mildewed Barley	0.0833		0.1143		0.1570	
Pine	0.0902	1.08	0.0864	1.13	0.1848	1.36
Poplar	0.0833		0.0764		0.1358	

A computer aided study of various IFOV values indicated that the gain in electron capture from a slightly larger aperture aided the sensitivity more than it degraded resolving power. This study supported the need to have a clear statement of system goals (low vs high contrast imaging, and the requirement for radiometric measurement vs limiting detectability). The system performance may be optimized by the selection of aperture size for each spectral band if required.

4.0 LABORATORY EVALUATION

Many of the results of laboratory tests and evaluation have been described as parts of the analytical and system descriptions, so will not be repeated here. We will describe some of the methods used in the laboratory and some of the results not reported in detail in previous sections.

4.1 Laboratory Test Equipment

The prime equipment developed specifically for the MSIDC is the optical bench test set shown in Figure 1-1. This versatile system consists of a rugged table on which the engineering model camera is mounted a fixed distance from the test scene. The camera includes the spectral filter unit and optics as they are used in flight.

The test scene is mounted on a vertical frame that is moved across the detection path at a rate corresponding to the rate of motion of a spacecraft or aircraft. The timing of the frame motion is controlled by the digital system that controls the camera scan, so that a precise distance of frame travel may be set for each line scan of the camera. This timing signal is applied to a stepping motor that drives a high precision ball screw for the frame motion. Typically fifteen steps of the stepping motor are required to move the frame the equivalent of one line in the scene. This has proven very successful in producing a smooth reliable motion for the test targets.

The frame is designed to hold transparencies as large as 18 by 18 inches, to cover the full field of view (22°) of the test lens. It is not necessary to illuminate the complete area, since the camera is fixed in position and line scans only an area approximately 1 inch by 18 inches. The frame motion is designed to move the complete test image past this lighted area.

The light source for the test stand consists of a line array of quartz iodide lamps driven by the 120 volt 60 cycle laboratory power source. This light source was aided by reflectors that increase the equivalent source, and by a water chamber that filters the infrared (heat producing) energy beyond the 1000 nanometers spectrum. Since the camera is focussed on the test object plane, the light source is out of focus, and can be adjusted for acceptable uniformity across the line scan. The choice of light source is a compromise of available sources, having an equivalent source temperature of only 2000°K, compared to a desired temperature of 5500°K for sun simulation. The equivalent light level at the object plane is a maximum of 2500 foot lamberts, hence is approximately one fourth that of maximum earth illumination. These factors must be considered in comparing laboratory to real world imagery.

4.2 Laboratory Test Results

4.2.1 Resolution

The resolution of the system was tested and demonstrated using a series of Air Force Test Patterns across the test frame. The limiting resolution under conditions of both high and low contrast scenes, could be determined with this system. The results are shown here for on axis tests using AF1951 Resolution Targets, the Bendix 502 lens and sensor tube S/N 037001.

Response Contrast	1778	1995	2257	2532	2840	3167
	Response at Elements/Diameter					
100 to 1	0.64	0.59	0.41	0.38	0.30	0.29
6.3 to 1	0.67	0.61	0.50	0.36	0.32	0.30
1.4 to 1	0.56	0.59	0.50	0.41	0.29	0.24

This indicates the ability to meet the requirements of the ERTS system requirement with at least 24% response at the equivalent of 200 foot ground elements. The off axis tests were not meaningful at this time because of aberrations in the lens. It is considered that this aberration is caused by the short lens to object distance (only 10X the focal length of the lens). Later tests of the tube alone indicate off axis performance that is degraded only slightly from that on center. A Schneider Xenotar lens, (100 mm, f 5.6) was found to have good off axis resolution, and was used for many of the wide angle tests. The image of Figure 1-3 was made using this lens.

4.2.2 Registration

The ability to control test scene position to less than one third resolution element, and to control the rate of motion very accurately, allows imagery to be generated in one or all colors. The most severe test of registration is the duplication of black and white tests patterns through the color process. Evaluation of resultant imagery from the color recorder by means of a microscope indicate that a combined aberration and misregistration is approximately one resolution element at the edges of the image. It may be noted in Figure 1-3 that the color quality remains high at the edges of the scene.

4.2.3 Sensitivity

Laboratory evaluation of the sensitivity factors in the system were made difficult by the factors of source temperature, filter characteristics of the heat shield, transmission factors of the test films used, and the characteristics of the optics, color separation filters and photocathode response.

Although the factors were analyzed and a light source figure determined, it was not considered completely reliable. The method found most dependable was the use of measured signal characteristics compared to tube sensitivity calibrations. The determination of photocathode current density gave an equivalent photometric measure of the input energy. Measurements of signal amplitude and noise content in video patterns correlated well with these calculations and were found to relate well to signal amplitudes resulting from actual sun illuminated targets and photometric measurement. A photocathode loading of 9 microamperes/ cm^2 was the most that could be achieved with the laboratory system. This is approximately half that expected from each of the color channels in space flight conditions, see Table 3-2. The laboratory generated color image of Figure 1-3 has a highlight signal to noise ratio of approximately 20 db.

4.3 Tube Development

The MSIDC program has been a continued progression of low budget tasks. Of these, the development of the tube was considered a major activity. The effort included several phases; the construction of one experimental multi-channel tube to gain experience toward

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later models, the construction of a tube having small dynodes and a potentially useful configuration, the construction of a final tube having a fiber optic face plate, and several experimental tubes having only one multiplier channel, but with experimental spectral filters on the inner surface of the faceplate. A tabulation of the tubes constructed is given in Table 4-1. The small number of tubes constructed is obvious, and the ease of construction is illustrated by the fact that the final tube S/N 027201 was made from an earlier tube S/N 056902 which did not have the necessary fiber optic faceplate. To further illustrate the reliability of the tube process, the final tube was damaged in shipment, repaired by laser welding, then reinserted in the flight model camera and used for the flight tests described in a later section.

Table 4-1 Tube History

Serial No.	Apertures/Spacing		Faceplate	Notes
126801	3	0.10	Plain	Experimental, Pool Uniformity
056902	3	0.10	Plain	Good
066901	3	0.10	Plain	Warped Dynode
126901	1	--	Plain	Internal Filter Experiments
126902	1	--		Internal Filter Experiments
126903	1	---		Internal Filter Experiments
126904	1	--		Internal Filter Experiments
037001	3	0.09	Fiber Optics	Good, Used in Operation
027201	3	0.10	Fiber Optics	Good, Backup, made from 056902

5.0 FLIGHT TEST EVALUATION

ITT Aerospace/Optical Division, Fort Wayne, Indiana has recently completed the aircraft flight testing of a Multi-Spectral Image Dissector Camera. This program, sponsored by NASA, was directed toward the requirements of the Earth Resources program. It shows great promise of fulfilling the objective of generating spectral data simultaneously in three color bands, extending from the blue to the near infrared. The data is produced in a manner that permits rapid production of color separation imagery, registered color imagery, and analog signal data.

The Multi-Spectral Image Dissector Camera System consists of an airborne camera unit,[1] an airborne magnetic tape recorder,[2] magnetic tape reproducer,[2] and high resolution color frame recorder.[1] An ITT strip film recorder was also used to generate continuous color separation films of each flight from which areas were selected for high resolution copy. This combination of equipment has been used to generate the imagery shown in Figures 5-1 through 5-9. The camera unit is shown in Figure 1-1. The ground station film recorder unit is shown in Figure 1-2.

Characteristics of the MSIDC are given in Table 5-1. The characteristics of the aircraft flights are given in Table 5-2. A block diagram of the system is given in Figure 5-10. A more detailed description is given in later sections. Significant and useful techniques are

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(1) NASA Property (NAS5-11617)
(2) Property of U.S. Air Force

described that reduced the effects of aircraft motion, aid location of a given area, and assist the operator in reproducing imagery.

- COMPOSITE COLOR IMAGE, MARYLAND -

The output from the multi-spectral camera is a continuous stream of video signals from each of three apertures that sample different portions of the optical spectrum. One of the unique features of the MSIDC is the unbroken feature of this imagery, as captured on the three parallel tracks of the on-board instrumentation tape recorder. Reconstruction of the scene is demonstrated in the scene of Figure 5-1. This picture taken from approximately 25,000 feet altitude is of the countryside from near Generals Highway, East to Mountain Point, and Sandy Point State Park on the Chesapeake Bay. The scene covers a strip 13 miles long and about 3 miles wide. The imagery is typical of near infrared film photography, made possible by the use of the S25 photocathode of the image dissector. One flight of the aircraft may last up to 60 minutes, (limited by tape recorder capacity), providing a strip of imagery as much as 400 miles long. The operation of the recorder is under pilot control, permitting selection of areas to be recorded.

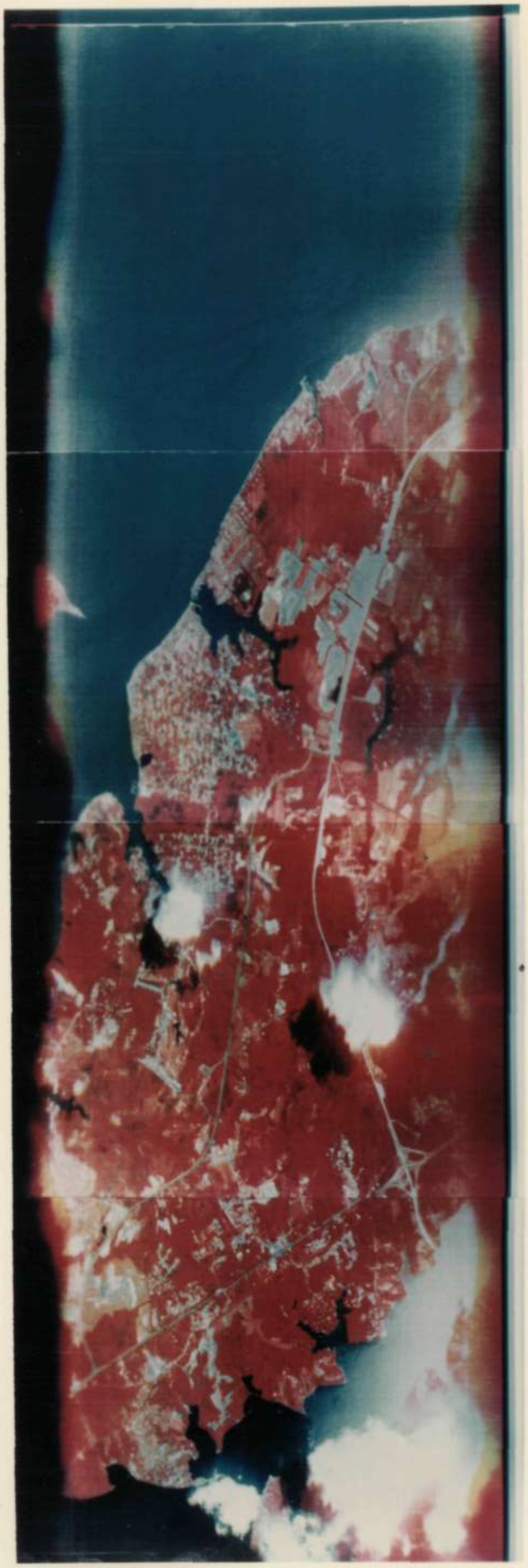

Figure 5-1. Composite Color Strip - Maryland

Photo No. 72-9-0068

- COLOR SEPARATION IMAGERY, RUSHFORD RESERVOIR -

The output from each selective aperture of the MSIDC may be printed as color separation images. Figures 5-2, 5-3 and 5-4, are of Rushford Reservoir Area, New York State. These were taken from an altitude of 50,000 feet on June 28, 1972. The differences in vegetation, urban areas, and roads are highlighted in the three spectral bands used. Figure 5-2 was reproduced from light filtered through the 480 to 585 nanometer transmission band. Figure 5-3 is the imagery from 585-685 nanometers, which is the normal red part of the visual spectrum. In Figure 5-4, we have allowed light from a narrow band beyond the visible, 715-775 nanometers, to be filtered to the sensing aperture. Here we definitely see the high reflectance of living vegetation and the sharp contrast to water bodies. This channel is especially useful for geographic study based on rivers, lakes and vegetation boundaries.

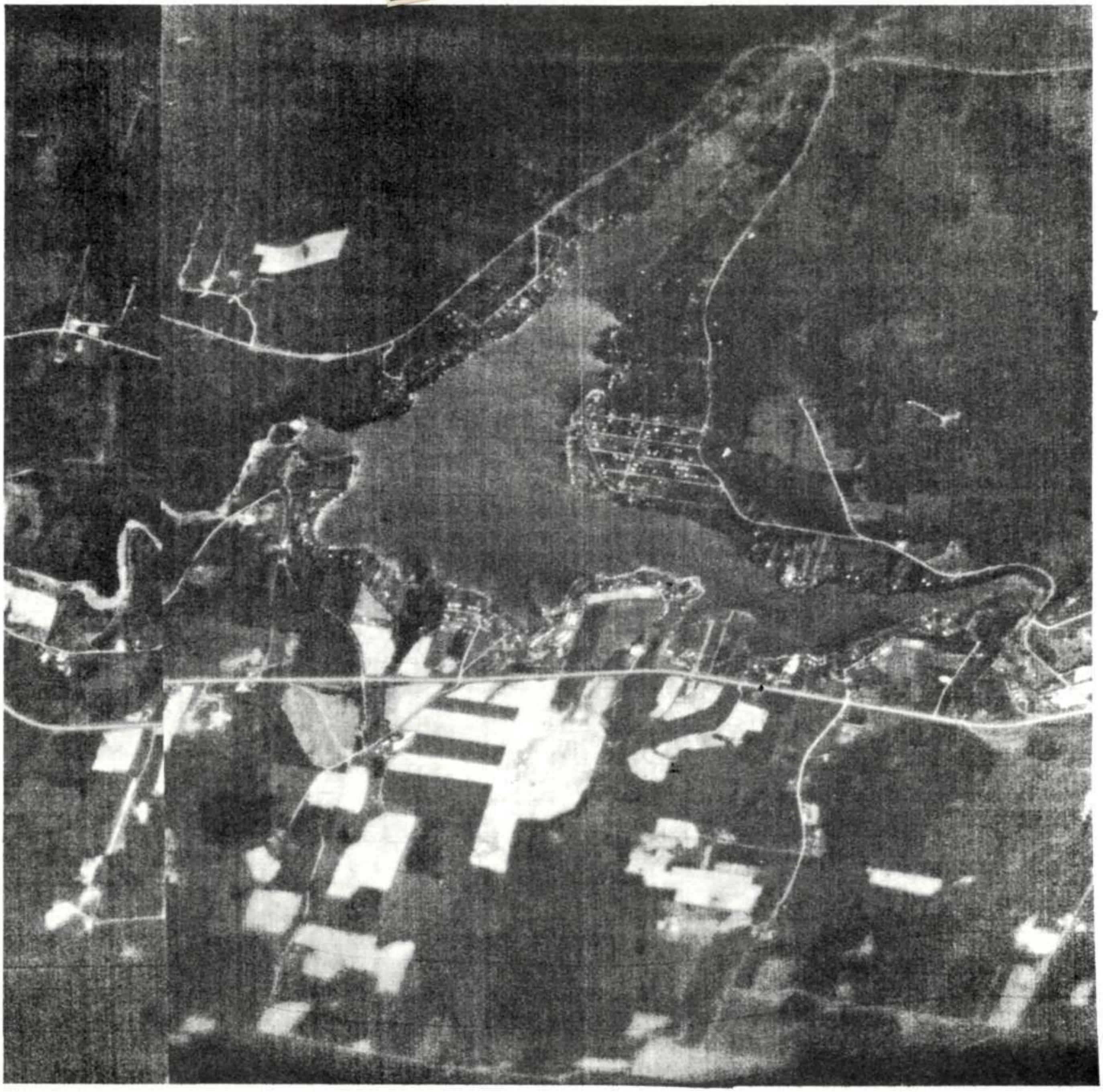

Figure 5-2. Color Separation - N.Y. 480 to 585 NM

Photo No. 72-9-0091

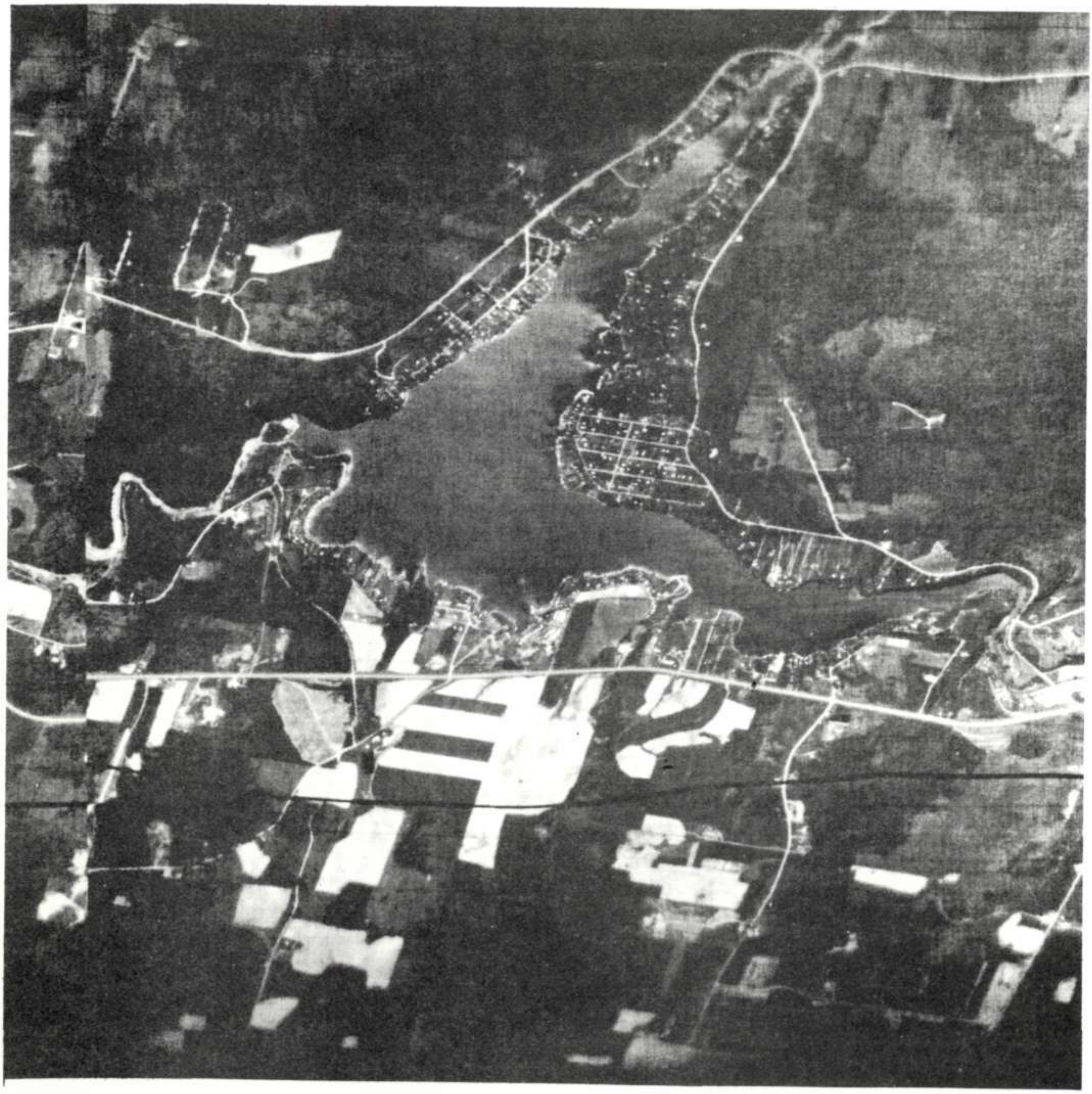

Figure 5-3. Color Separation - N.Y. 585 to 685 NM

Photo No. 72-9-0093

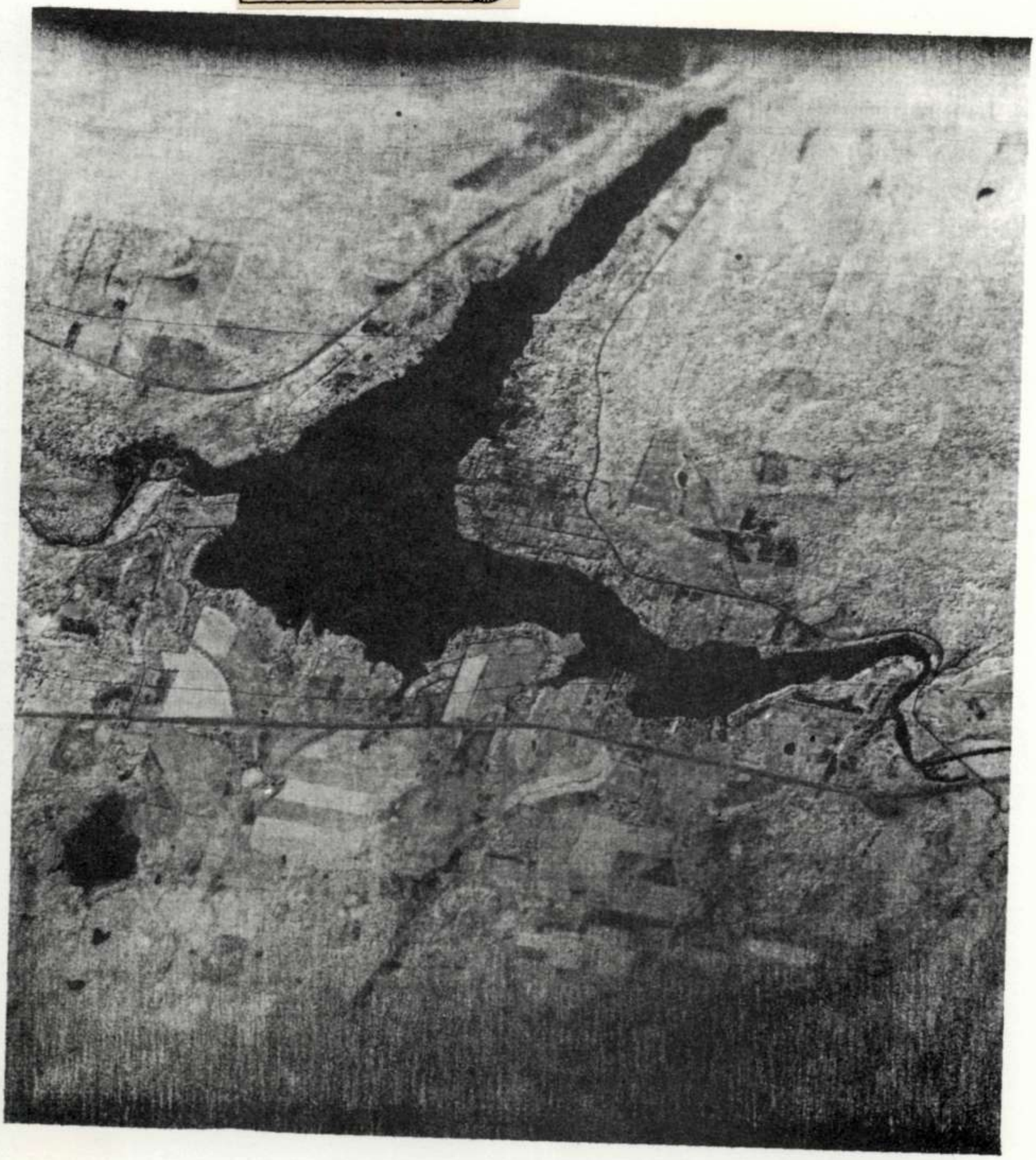

Figure 5-4. Color Separation N.Y. 715 to 775 NM

Photo No. 72-9-0094

COLOR SEPARATION AND COMPOSITE IMAGERY, WASHINGTON BELTWAY

In these pictures, taken in June 1972, from approximately 25,000 feet over the intersection of Rt. 495 (Washington Beltway) and Rt. 95 (Washington-Baltimore Parkway) we see a region of heavy urbanization with some vegetation and Greenbelt Lake. The color separation images (Figures 5-5, 5-6, 5-7) are in the same sequence as before. In addition we have expanded one image, Figure 5-8, to demonstrate the high resolution of the system. It may be noted that objects of a 4 foot cross section are detected in this photo. The camera has a resolution of 3000 TV Lines which is only slightly degraded in the recording and reproducing process.

Figure 5-9 is a composite color image from the three color separation channels. This is a direct color recording process using a frame annotation system on the tape recorder and sequential color recording directly from the tape record to a color film. The image demonstrates the high degree of resolution and registration inherent in the MSIDC principle.

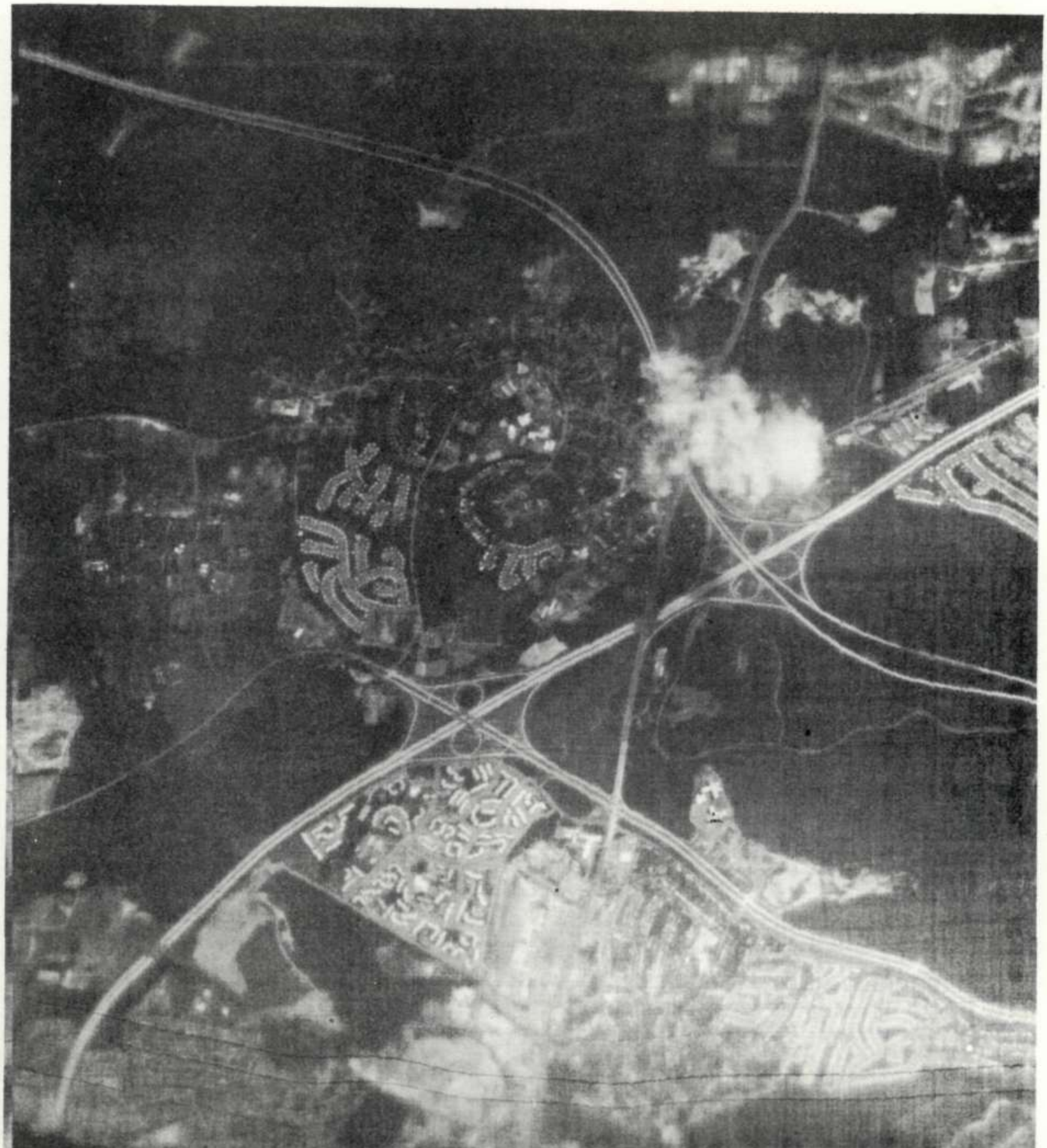

Figure 5-5. Color Separation - D. C. 480 to 585 NM

Photo No. 72-9-0090

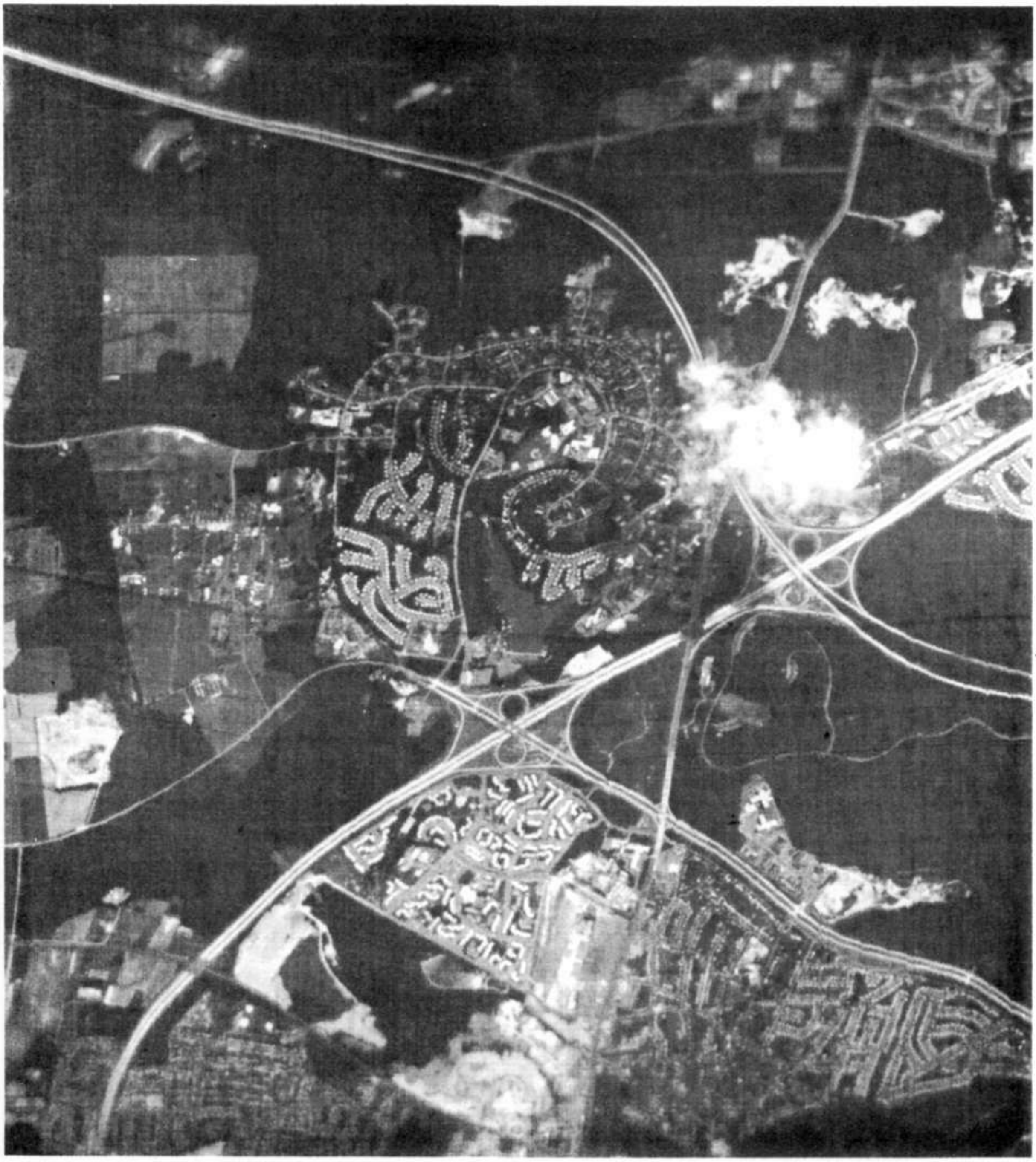

Figure 5-6. Color Separation - D.C. 585 to 685 NM

Photo No. 72-9-0095

Figure 5-7. Color Separation - D.C. 715 to 775 NM

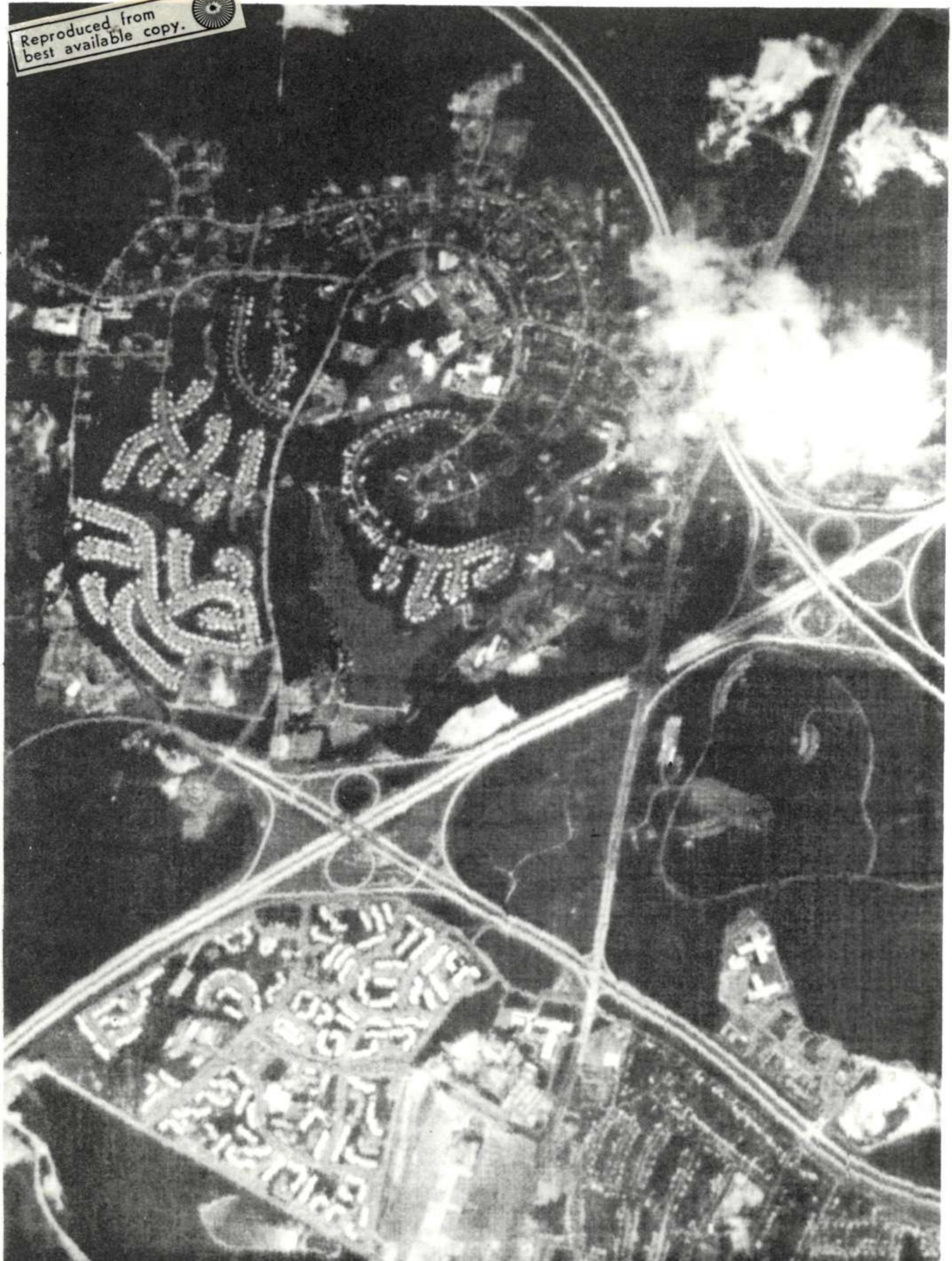

Figure 5-8. Expanded Color Separation - D. C. 585 to 685 NM

F

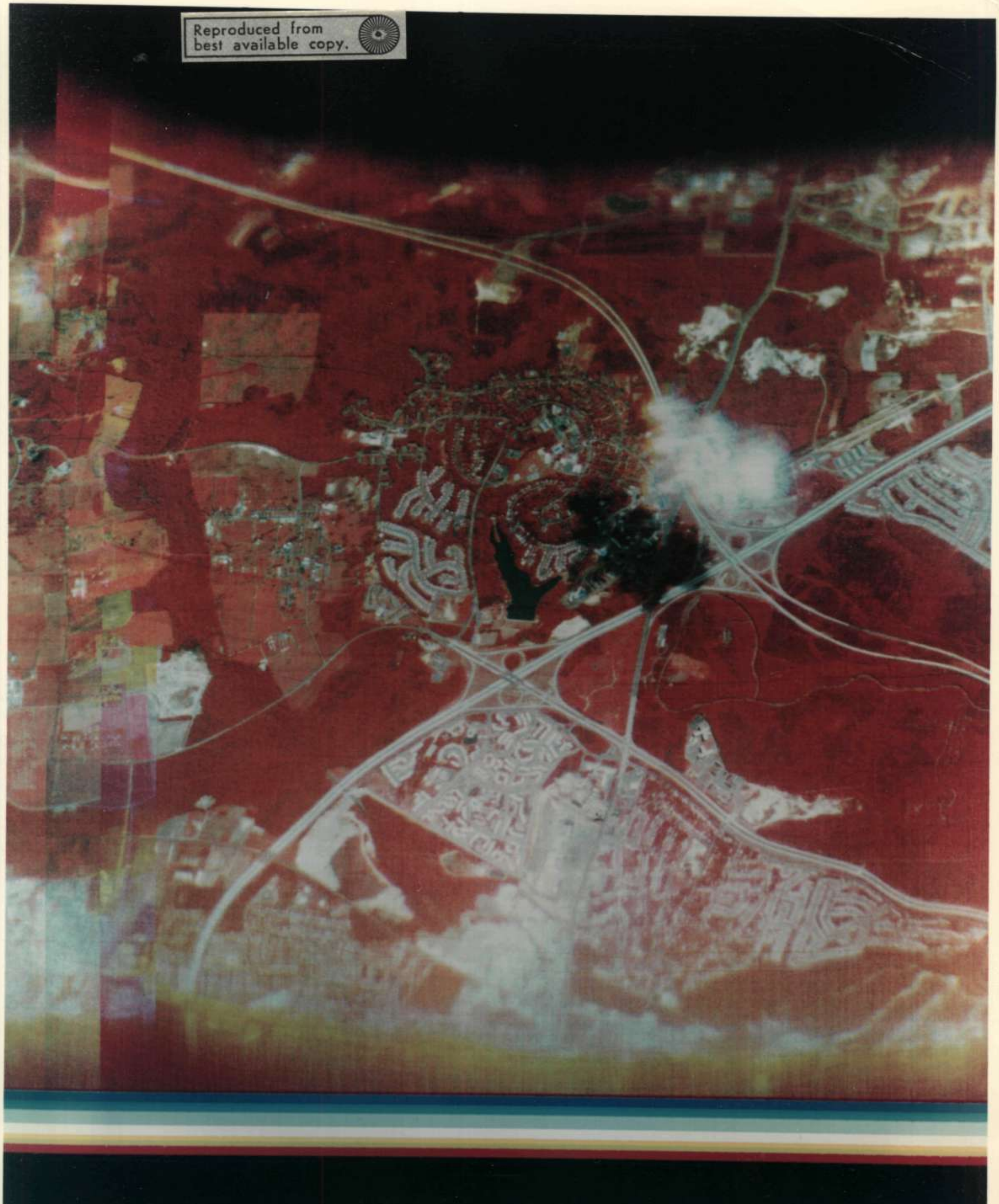

Figure 5-9. Composite Color - D.C. - Greenbelt

Photo No. 72-8-0006

MULTI-SPECTRAL CAMERA

The MSIDC is shown in Figure 1-1 on a laboratory test stand prior to flight. In the laboratory the system line scans a moving test pattern. The single camera and optics as shown are capable of generating the three simultaneous color outputs. In the flight configuration an inertial gyro unit is added to the system, providing a roll compensation signal that is instantaneously applied to the magnetic scan of the camera. The flight images show the success of this compensation, where roads are shown to be undistorted, while the effect of roll can be detected by slightly wavering lines caused by dirt that may have been trapped at the tube-filter interface.

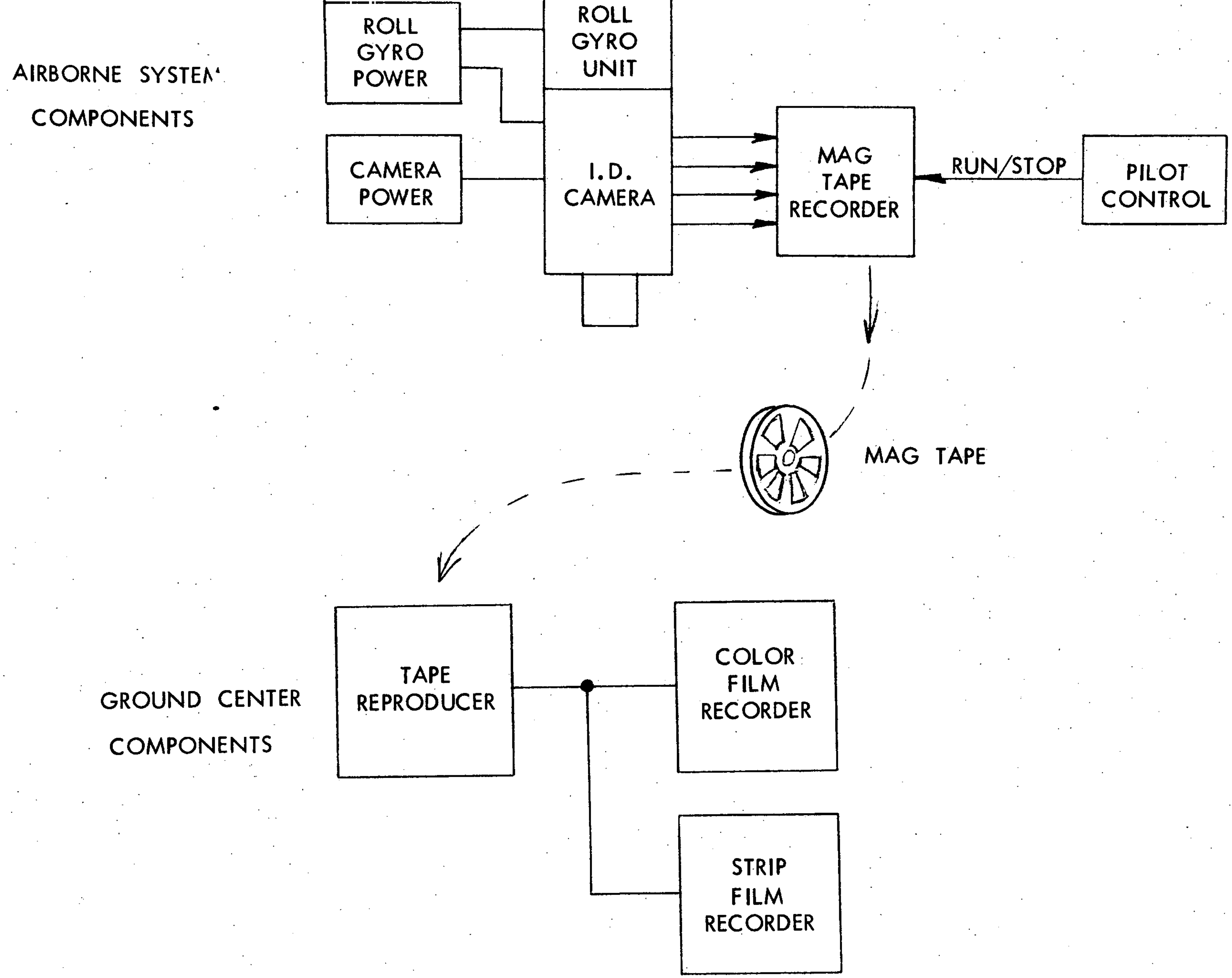

Figure 5-10. Multi-Spectral System for Airborne Operation

- COLOR FILM RECORDER -

Data from the camera or the magnetic tape recorder is reproduced in the unit shown in Figure 1-2. Making use of the frame annotation recorded on the tape, the high resolution CRT first records a frame of imagery from one color by line scanning through an appropriate color filter to a moving film holder. For composite color images, the tape is replayed, the frame start signal detected, and the data from the second channel applied to a line scan and a second color filter. This is repeated for the third color, permitting registered images to be recorded on Polocolor film, Ektachrome, Ektacolor or other film as desired.

This recorder is limited to making reproductions of segments of the recorded imagery, but has been very successful in demonstrating the registration characteristics and quality of the imagery. As shown in Figure 5-1, the successive images may be combined to reproduce a continuous strip of a selected area.

The program sponsored by NASA began in 1968. The first laboratory generated color imagery was shown in late 1970. Flight tests by the USAF, Rome Air Development Center, were conducted in March and June 1972. The USAF provided a high altitude aircraft and crew. ITT activity was funded by NASA.

Recognizing that the system tested was only intended to be a laboratory evaluation model, the performance under flight conditions was both an evaluation and a learning experience. From this experience we are able to relate results with initial goals.

The Image Dissector sensor and the approach to color separation are practical and reliable concepts that may be applied to operational systems.

The sensor resolution has been demonstrated in laboratory and field tests to be capable of 3000 line image generation.

The sensitivity of the system agrees with the calculations of input flux, optical degradation by the lens and filters, and the operating parameters of the system. This now permits extension of the concept to other airborne and space applications with a high degree of confidence and the ability to relate proposed system quality to that of actual experience.

The registration of color imagery to an accuracy of 0.05% on direct reproduction of imagery from the camera has been demonstrated by lab tests and appears to be occurring in the reproduction of flight imagery. This is very significant in that no computer processing, image matching or other sophisticated techniques are required to reproduce the data. This infers that high quality color imagery may be printed in real time from an aircraft or satellite operation.

The ability to adapt camera parameters to aircraft velocity and altitude conditions has been proven by flights under various conditions. The control for these adjustments were set manually before flight, but could be pilot operated, remotely commanded, or automatically set.

The ability of on-board sensors to detect aircraft roll was demonstrated and the ability to introduce the roll correction directly into the scan system of the camera was demonstrated. Although not required in a high stability satellite, this method could be adapted to a low stability satellite, and is a definite advantage in the airborne operation of the multi-spectral camera.

The development of the MSIDC to the present state has been accomplished at a relatively low cost. The complete development including new tube development, camera design and fabrication, test bed construction, color film recording unit, and all flight integration and support have been completed for less than $500,000.

From the success of the program it is evident that the system has met the requirements of the original goals, and that the system has proven itself in a near operational environment. We recommend that this system be considered a candidate for satellite and aerial observation.

Table 5-1. MSIDC Characteristics

Camera Unit

Optics	100mm, f/0.95, Bendix Model 502
Spectral Filters	Deposited, interference type (Laser Energy, Inc.)
Spectral Response (Filter Only)	495-585 nanometers 580-700 725-950
Spectral Response (Tube & Filter)	495-585 nanometers 585-685 715-775
Sensor Tube	ITT F-4082, S/N 037001 S25 Photocathode Fiber Optic Faceplate Three apertures, 15 micrometer dia., 0.083 inches apart Separate electron multipliers Magnetic Deflection Magnetic Focus
Resolution, Limiting	Greater than 3000 TV Lines
Scan Rate, Swath Direction	4 to 140 scans per second, with automatic roll compensation
Vertical Scan (Track)	None
Camera Video Bandwidth	0 to 250 KHz
Timing Control	Crystal Oscillator, 24.25 MHz
Focus	Second Loop with Dynamic Focus
Output Signals	Red Video, analog Green Video, analog Blue Video, analog Continuous clock pulses with sync and frame number amplitude coded

Table 5-1. MSIDC Characteristics (Continued)

Roll Detection	Vertical Rate Gyro, Honeywell
Pitch Detection	Vertical Rate Gyro, Honeywell
Pitch Signal Insertion	Calibrated DC offset in vertical (Not used in present tests)
Camera Unit Components	
Camera less Lens	9 x 9 x 18 inches 45 pounds
Lens	6 in. dia. by 6 in. long 9 pounds
Camera Control Unit	9 x 18 x 10 inches 35 pounds
Gyro Assembly	2 x 2 x 5 inches 1 pound
Gyro Power Unit	2 x 3 x 9 inches 4 pounds
Gyro Control	2 x 3 x 6 1 pound
Total System Weight	95 pounds
Total System Power	1.3 Amps., 115V, 60/400 Cy.
Tape Recorder Unit (USAF Property)	
Model	3M model 110
Tape	7 track, 1 inch, 9200 ft. long
Tape Speed	60 inches per second

Table 3-1. MSIDC Characteristics (Continued)

Time/reel	1 hour
Recording Method	FM, DC to 500 KHz
Size	12-1/2 x 17-1/2 x 21 inches
Weight	100 pounds
Power	500 VA
Tape Reproducer (USAF Property)	
Model	CDC Model VR3600
Strip Film Recorder (ITT Property)	
Kinescope	Line Scan High Resolution CRT
Recorder	35mm strip film camera DC speed control
Output	35mm Tri-X Monochrome Film One half hour flight time on one film strip
Color Film Reproducer (NASA Property)	
Kinescope	Line Scan High Resolution CRT
Recorder	Polaroid Film Pack Digital Driven Vertical Position
Color Separation, Electrical	Vertical Line Separation
Color Separation, Optical	Strip Gelatin Filters
Resolution, Limiting	Over 4000 TV Lines

Table 5-2. Aircraft Flight Test Conditions
(Typical)

Altitude	50,000 feet
Velocity	300 Knots
Swath Width	20,000 Feet
System Resolution	
IFOV	150 microradians
Limiting	120 microradians
Ground Resolution	6.7 feet per element 13 feet per line pair (GRD)
Camera Scan Rate	70 scans per second

5.1 System Operation

The camera is oriented in the aircraft so that the scan is at right angles to the direction of flight. The scan rate is chosen so that a scan is generated each time the aircraft subpoint advances one resolution element on the ground. Contiguous scanning is thus produced. Each of the three apertures, therefore, produced a continuous strip map of the earth's surface as seen in a chosen spectral band. Since the lines scanned on the photocathode by the apertures are displaced from one another, the lines scanned on the scene will be displaced a proportional amount. This displacement is along the line of flight, causing a line on the earth scanned by one aperture to be scanned by the second aperture a given time interval later and by the third aperture a similar period after that. This spatial displacement must be compensated for in order to place the three pictures in registration.

The method used to correct the registration of data is dependent on the technique to be used in analyzing the data. For example, if data is accumulated and stored in the form of three separate transparencies, registration can be obtained by simply offsetting the transparencies one from another by a pre-determined number of scan lines. If a composite color picture is to be produced, registration is achieved by line scanning a CRT equipped with strip color filters (properly separated to match aperture separation in the camera) and using a time-shared single beam. The method used in our ground station recorder requires the film to be passed in front of the CRT three times to add the color components to a film. A future method could use a three beam CRT.

Roll of the aircraft is compensated in the camera assembly, reducing registration errors due to this component of aircraft motion to a very low level. A vertical gyro senses the aircraft roll. Its output is fed into the deflection amplifier in the correct sense and ratio to exactly counter the roll. In the aircraft flights to date this has performed very successfully. In a spacecraft stabilized to 0.01^{o}/sec. roll there is no need for such correction.

5.2 Sensor Characteristics

The sensor used in this camera is a modification of the standard ITT F4052.

The modification of the F4052 from the single aperture to the three aperture configuration has not resulted in any degradation in tube performance. In the line scan mode, nearly the whole 1.75 inch photocathode diameter can be used. The resolution obtainable is 3500 TV lines at 25 percent. The response of the S25 photocathode is shown in Figure 3-3. While the S-25 does not have the peak "blue" sensitivity of the S-11 or the S-20's, its superiority at increased wavelengths is obvious. Further, it surpasses the S-1 out to beyond 900 nm. From the standpoint of spectral response, the S-25 is clearly the best photocathode for the earth resources application and highlights the presence of man-made features among natural vegetation. The imagery of Section I shows the characteristics of this response.

Figure 5-11 illustrates the actual conditions as present in the MSIDC flight program. From this we see that the results are far from ideal, resulting in transmission bandwidths much less than the desired goal. The half amplitude sensitivity frequencies therefore result in spectral bandwidths of 495 to 585 nanometers, 585 to 685 nanometers and 715 to

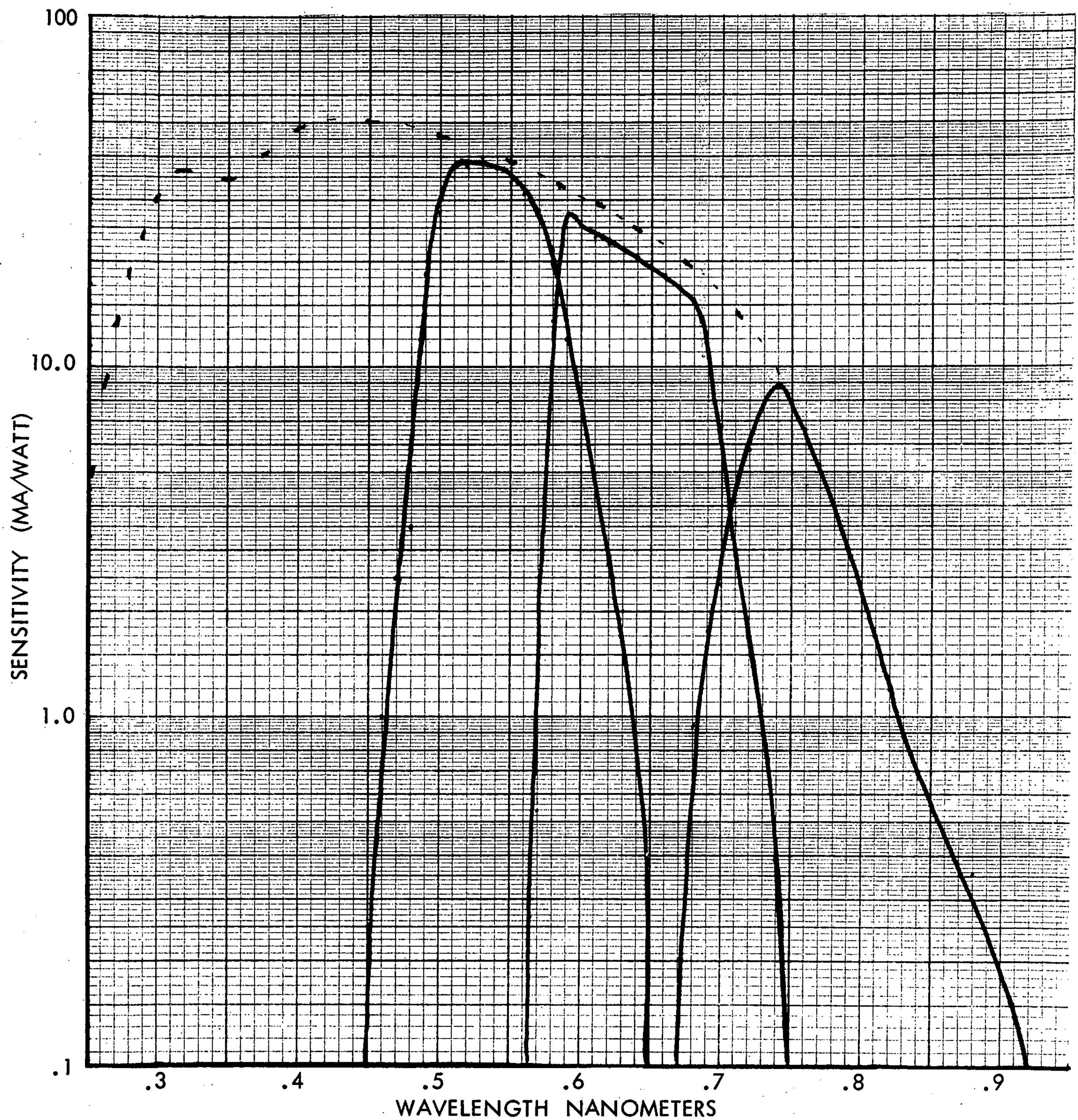

Figure 5-11. EEM Camera Spectral Sensitivity

775 nanometers. The red spectrum is still beyond visible and highlights vegetation, but does not have the amplitude nor bandwidth that might have resulted from a fully capable sensor tube.

5.2.1 Data Processing

The signal level output from each camera channel is set to a normalized level by photometric calibration from a white target. An electrical grey scale signal is then inserted during each line scan to maintain calibration for faithful reproduction. Three tracks of the tape recorder therefore contain composite video, black level reference, and a four shade grey scale. A fourth channel records a digital clock signal from the camera, from which line scan rate, deflection and all timing functions are derived. A pulse amplitude code at the beginning of each line assures line synchronization, and a frame number code at the beginning of each line identifies the time of event. This frame code changes every 2048 lines, providing a key to the generation of synchronized images of a chosen segment of the record. The reproducer has the ability to recognize any chosen frame for the beginning of a film recording sequence. Once physical and electrical alignments are complete, no further signal processing is required to reproduce an image from a normal flight.

5.3 System Results

A goal of approximately 3000 TV Lines per diameter was set to match the requirements for 200 foot elemental resolution from the ERTS spacecraft (496 n mile altitude and 100 n mile swath width). The laboratory tests have shown this to be achieved from test pattern input. Resolution of Air Force Bar Targets of high contrast indicate 25% MTF at 3200 TV lines. In order to achieve this resolution we have included a special design of deflection coil and focus coil that shape the fields for uniformity, made use of second loop focus, and have selected a 15 micrometer aperture. The tube faceplate is made of fiber optics of 5 micrometer diameter, contributing very little degradation to the image. The inclusion of deposited color filters in the optical path causes some dispersion and contributes to degradation, and the optical qualities of the lens both on axis and off axis contribute to the resolution characteristic. In a future operational system it is possible to improve each of these factors slightly and regain some of the quality inherent in the pickup tube alone.

5.3.1 Sensitivity

The output film image is the result of the quality factors of the complete system. From the scene we collect energy at high efficiency with a large aperture lens (T/1). Added loss in the fiber optic faceplate, and accelerating screen of the tube reduce the collected energy to less than 30% of that available to an ideal system. Even with these losses, the signal from the tube is well above amplifier noise and remains limited only by the random noise of the signal electrons. Characteristically, the camera scans at a rate of approximately

70 scans per second. From a normal ground scene of 3000 foot lamberts (about that shown in Figures 5-1 to 5-8) the system has a potential signal-to-noise ratio in each channel of 20:1 or 26 db in the highlights. Signal-to-noise ratio of the camera in each channel is approximately 12.2, 12.2, and 6, mostly as a result of the tube spectral losses. Unfortunately, the pictures displayed were taken from a tape recorder and reproducer combination which do not have a very low noise figure, resulting in system signal-to-noise ratios of 9, 12, and 6.

A self-test system is included in the camera unit, where a reference signal of a known amplitude is inserted in the output at the beginning of every line, and a four level grey scale pattern is inserted in the video to check the system.

An effect noted in the imagery of Figures 5-1 to 5-7, is the shading of the image from edge to edge. Much of this is contributed by the lens, which was designed for a smaller image plane than the 1.75 inches of photocathode being used. Some shading is contributed by the tube photocathode as the result of physical damage that occurred in shipment of the system. Rough handling of the camera caused the accelerating screen to be dislodged. Because of a short repair time before the next flight, it was repaired by laser welding which contaminated the surface in the area of the weld. This is most notable in the red sensitivity loss at one side.

A wider angle lens and a new tube would make the picture very uniform, equivalent to that of a photographic system.

5.3.2 Stability

The ability of a flight camera to operate over a long time period at various altitudes and temperatures, yet maintain optical and electrical focus, and not change in scan rate, sensitivity or other factors is demonstrated in this system. The camera and tape recorder power were turned on before the aircraft took off. The only control during flight was the stop and start of the tape motion system for recording or not recording. After filling the tape (approximately 60 minutes flight) the pilot returned to base where the equipment was turned off.

Contributing to this stability were many hours of design and test of highly stable focus current regulators, deflection amplifiers, and power supplies. The image section power supply operates from its own regulator that is floated in voltage above the regulated dynode voltage supply. Circuit voltage supplies were selected for high stability as well. The reliability and stability of the system is demonstrated by returning to optical spots to an accuracy of one part in 6,144.

5.3.3 Scan Control

The multi-spectral camera operates from a basic digital clock from which all synchronizing and scan signals are derived. A selection of divisor elements permits a choice of scan repetition times from as low as 4 scans per second to 100 scans per second. Each scan is made up of 6144 elements, with a digital to analog conversion before the final amplifier that controls the deflection current. A feedback current signal is compared to the input signal to insure linearity of scan position. The linearity of scan is within 0.02% with this type of control.

The output of the camera includes three lines of video and one line of clock signal. The clock line is a digital string at the elemental scan rate. At the beginning of each scan the amplitude is increased 50% for a string of 16 elements, which can be recognized as line sync. In addition, at the end of every 2048 scan lines a separate digital code is inserted that indicates a frame number. This number is detected in the film recorder and displayed on a numerical display. A preset counter on the display may be set to select any frame number such that the beginning of that frame will trigger the film reproducer mechanism, making a copy of that particular frame of imagery.

5.3.4 Color Registration

Controls are included in the film recorder unit that provide alignment of the signals coming from the camera. Electrical adjustments to compensate for differences of aperture separation, horizontal offset and differing distortion from side to side are provided. Since the CRT system is set up electrically, all of these features can be included. Again, using the digital baseline, the vertical separation of scans related to the three colors can be adjusted precisely for the camera in use. Static offset horizontally can be set also. In addition we provide dynamic control of the vertical position along each of the three scan lines to compensate for geometric distortions in the camera. The result is a stable alignment that permits duplication of imagery over a long period of time with no need for realignment. The output pictures are excellent in this respect. Test imagery has shown that the combination of optical chroma and misalignment contributes less than one element of edge effects at the sides of the image. Since the system is horizontally symmetrical and all motion vertical is related to film motion only, there is no change of alignment or quality in the vertical direction.

5.3.5 Color Film Reproduction

Selection of a reproduction process was determined by the need for flexibility in scan control, position control, selection of color filters, the use of convenient output film types and high quality. Our use of a high resolution single gun CRT has proven effective. The line scan on the CRT is positioned vertically for each of the color inputs. This offset, when coupled to the film, compensates for the aperture separation, permitting direct reproduction on a Polacolor or Ektrachrome film. The output from a tape track is fed to the CRT, which scans the appropriate position on the tube face. The CRT output is optically coupled to a film plane where the film holder is in a vertical mount. This mount is driven by a high accuracy Ball screw from a stepping motor. Advancement of the stepping motor is controlled by the derived clock signal that was recorded with the video. After recording an image from the red channel the carriage is returned to the initial position to within one elemental position, then the second color imposed on the film. After the third color is recorded, the film may be removed and processed normally.

Adjustment of the output position for each color channel is performed when the aircraft has flown with a yaw (crab). This required a controlled offset of the scans during the film reproduction process. If a yaw sensor were available on the aircraft this could be recorded and used to automatically correct the copy process.

One limitation of the film reproducing system is its dependence on individual frames of imagery. In order to record a full strip of imagery that relates to the total flight of the aircraft we make use of a separate, lower quality CRT line scan recorder that has a strip film (35 mm) attachment. This is a convenience in that a total strip will permit selection of areas of interest for high resolution or color recording.